DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH
875 NORTH RANDOLPH STREET
SUITE 1425
ARLINGTON, VA 22203-1995

IN REPLY REFER TO:

5720
Ser BD042/035
ONR FOIA 16-013
January 27, 2016

Ms. Elizabeth Miller
248 Maynard St. #2
Santa Fe, NM 87501
503-866-4584

Ms. Miller:

This is the final response to your Freedom of Information Act (FOIA) request received by the Office of Naval Research (ONR) on November 19, 2015. You requested "a copy of a report completed for ONR that tested various water filtration devices on their ability to meet the demands of the NSF P248 and filter water for use during backcountry travel." We assigned your request ONR FOIA number 16-013. A copy of your request is included with this letter.

We have classified you as a "media" requester. As such, we may charge you for some of our duplication costs, but we will not charge you for our search or review costs. You are also entitled to receive up to 100 pages of photocopies (or an equivalent volume) for free. We have located 52 pages that are responsive to your request. Accordingly, there is no charge for this request.

Parts of the records you requested have been redacted under Exemption 4 of the FOIA. Exemption 4 protects "trade secrets and commercial or financial information obtained from a person [that is] privileged or confidential" 5 U.S.C. § 552(b)(4). Per our review standards, we are withholding contact information of key personnel, specific drawings, design descriptions, material selections, manufacturing techniques, and future suggestions for product improvement. We have attached a copy of the releasable records with the above mentioned redactions. Since you indicated you are willing to accept clearly releasable information, we do not consider these redactions to be a denial or partial denial of your request.

If you have questions about this letter, please feel free to contact Ms. April Harrid at (703) 696-4309 or ONRFOIA@navy.mil. Please reference ONR FOIA 16-013 when communicating with us about this case.

Sincerely,

Edward Orlowsky
Director
Management Service Division, BD042

Attachments:
As stated

Final Report

For

Solicitation/BAA Number: ONR BAA 11-007

“Flat Filters for Water Purification at the Individual Warfighter Level”

Contract Number N00014-12-C-0140

Report Submitted by:

Cascade Designs Inc.

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25th February 2015

Executive Summary

Water logistics is one of the major issues and costs in supporting troops in the field. For forward deployed warfighters operating in a hostile environment, the ability to capture water quickly and then treat the water under the cover of safety away from the source is critical. Therefore, any water purification system at the individual warfighter level must minimize the exposure when gathering water, and purify it away from the source to remove any contaminants (i.e. enable a true “scoop and go mode” of operation). Consequently, the U.S. Office of Naval Research (ONR) is seeking an advanced water purification system that is superior to the individual disinfection technologies (i.e. MSR MIOX Purifier and MSR Microfilter) that are currently being fielded.

Cascade Designs, Inc. believes that the best approach for removing all microorganisms that may be present in surface and ground water sources, without altering its palatability, is the use of a physical barrier. Therefore Cascade Designs’ effort was based on the development of an Individual Water Purification System (IWPS) that incorporated both size exclusion filtration (ultrafiltration/microfiltration membrane) and adsorptive media into a flat-filter design which would be capable of being incorporated into a tactical hydration carrier.

The initial work was based on surveying available flat sheet treatment technologies and evaluating them in order to down select to the most promising options. This ultimately yielded one ultrafiltration (UF) membrane option and two different microfiltration (MF) membrane options. Explorations during this task also led to the validation of a flat sheet activated carbon material which vastly outperforms the granular activated carbon used in the MSR Microfilter in the current IWPS. These components performance were then benchmarked in a breadboard configuration against NSF P248 and shown to effectively remove all microorganisms in both GTW1 and GTW2 while maintaining promising flow rate and capacity characteristics.

Following this breadboard evaluation, several alpha prototypes were fabricated and tested in order to evaluate potential internal structure materials and fabrication methods, as well as to quantify the selected materials performance against NSF P248 in a laboratory setting. Over 40 different internal structure materials were down selected before a polypropylene mesh product from DelStar was chosen as the best available option. Combining several layers of this material allowed for the most favorable ergonomic design while also providing little flow restriction. Alpha prototypes were shown to be effective in removing all microbes, improving upon IWPS flow rate and capacity, as well as exhibiting increased resistance to freeze/thaw and drop damage. With the total design options narrowed to 3, development progressed to beta prototype fabrication.

During this phase of development, several iterations of prototypes were built with each of the three selected rejection membranes. Testing at this stage revealed several necessary modifications. First, at this larger scale, a flexible interim layer was necessary to ensure filter durability as creases/wrinkles were more likely to develop. Second, fabrication of the UF

prototype with the selected adhesive required application by hand, which meant additional development, would be required prior to progressing to low rate initial production (LRIP). Finally, the elongated shape of the filter, used to maximize available surface area, resulted in an increase in flow restriction. This final challenge was overcome with the addition of a central, perforated, tube which provides a water collection space and channel through which treated water can pass to the drink port. Once these critical issues were resolved, each of these beta prototypes were benchmarked against NSF P248.

Both of the MF prototypes exceeded the performance of the MSR Microfilter included in the current IWPS in the areas of flow rate (2 L/min vs. 1.2 L/min) and capacity (>1000L vs. 300L) while also maintaining microbial reduction targets. The UF prototype did exceed the minimum flow rate spec of 200 mL/min with a flow rate of 350 mL/min, but this was still lower than originally hoped for. This filter configuration did reach a capacity of 300 liters with aggressive cleanings and was shown to be a true “scoop and go” single pass purifier. The disappointing flow rate performance of the UF prototype led CDI to request additional funding for exploration of the use of a higher flow rejection layer in combination with adsorbent sheet technologies in order to achieve the same goals, but at a faster flow rate.

This project extension was granted and, after down selection, a breadboard prototype was built and evaluated in accordance with NSF P248. A significant improvement in flow rate was gained over the UF beta prototype (829 mL/min vs. 350 mL/min) and a total of 269 liters of GTW1 was treated while maintaining the desired log reductions. However, upon switching to treating GTW2 (10mg/L TOC; ≥ 30 NTU) the log reduction of virus fell below the desired 4.0 LRV after treating just under 20 liters of this highly contaminated feed water.

Through the efforts of this project significant advancements were made in flow, capacity, durability, and ergonomics with the MF beta prototype design. Development growth towards a flat-filter design capable of acting as a single pass purifier was also made. However, the lower flow of the UF beta prototype, and sensitivity of the rejection/adsorbent combination breadboard to high concentrations of organics, result in the need for more development prior to commercialization. Still, Cascade Designs has strong reason to believe that with the development of a natural organic matter (NOM) pre-filter, this combination rejection layer/adsorbent layer approach could prove to be the fastest flowing, most ergonomic, “scoop and go”, single pass, man-portable water purifier to date.

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1 Project Background

1.1 Overview

Water logistics is one of the major factors and costs in supporting troops in the field. Depending on climate and mission requirements, a soldier in the field needs to drink from 4 to 15 L per day to avoid dehydration. Consequently, the Marine Corps Systems Command (MARCOSYSCOM) has established the need for individual water purification systems that will allow forward deployed warfighters to convert all fresh water into microbiologically safe drinking water. The water purification approach that is currently being fielded by the Marine Corps at the individual warfighter level is based on the integrated Individual Water Purification System (IWPS) developed by Cascade Designs (CDI). The IWPS kit developed at CDI under a SBIR program is comprised of an ILBE compatible hydration carrier which houses a 3 L hydration reservoir, a MSR MIOX Purifier (handheld electro-chlorinator), and a MSR IWPS in-line filter. The in-line filter is mounted on the drink tube and consists of a 0.2 μm microfiltration hollow fiber cartridge upstream of a granular activated carbon packed bed. The MF filter removes turbid matter, bacteria and protozoa while the carbon media improves the taste of the filtered water by removing the residual oxidant in addition to dissolved organics and some heavy metals.

Despite the numerous advantages of using the MSR IWPS in-line filter to purify water on the battlefield, this approach has several limitations that inhibit its widespread implementation. First, the use of a microfiltration hollow fiber membrane makes the filter prone to freeze/thaw damage once it has been used in the field. This is because the structural integrity of MF hollow fiber membranes is compromised during freeze/thaw cycling by a macroscopic fiber breakage issue. Second, the pore size of the microfiltration hollow fiber membrane (0.2 μm) is larger than virus particles (0.02-0.05 μm) and therefore any viruses present in the contaminated water source must be removed by a chemical disinfectant. This chemical addition step prevents the IWPS kit from providing a true “scoop and go” water purification approach (i.e. a hands-free device that can purify surface water away from the water source). Third, the rigid form factor of the MSR IWPS in-line filter makes it less than ideal from an ergonomic perspective when mounted inside an ILBE compatible hydration carrier.

This report summarizes how Cascade Designs developed a paradigm shifting approach for on-the-move water purification at the individual warfighter level that addresses all of the aforementioned shortcomings of the IWPS kit currently being fielded by the Marine Corps. In contrast to all other ILBE or MOLLE compatible water purification systems, our effort was based on developing a lightweight and compact filter that is specifically designed to be placed *inside the hydration bladder* instead of being *mounted externally on the drink tube*. By making this simple switch in where the filter is mounted in the ILBE hydration carrier, we are no longer constrained by the use of a ***rigid tubular filter housing***. Mounting the filter inside the 3 L hydration reservoir indicates that the ideal form factor for the proposed filter is a ***flexible rectangular filter*** that is only a few tenths of an inch thick.

1.2 Technical Approach

Overview of Individual Water Purification Systems Fielded by the Marine Corps

The warfighter's need for unrestricted movement on the battlefield presents a challenging situation for conventional water treatment methods. Depending on climate and mission requirements, a warfighter on the battlefield needs to drink from 5 to 15 L per day to avoid dehydration. Chronic dehydration can lead to such problems as fatigue, kidney stones, urinary tract infection, rectal afflictions and skin problems, as well as long-term health problems, including kidney damage. For forward deployed soldiers operating in a hostile environment, the ability to capture water quickly and then treat the water under the cover of safety away from the source is critical. This means that the water purification process should be performed away from the water source and thus minimize the exposure of the soldier to hostile actions when gathering the source water (i.e. enable a true "scoop and go" mode of operation). Furthermore, the water purification system must be able to remove a diverse range of chemical (e.g. heavy metals, industrial pollutants) and microbiological contaminants that may be encountered on the battlefield.

However, water treatment products designed specifically for the outdoor and travel markets are generally not compatible with the military's on-the-move hydration systems. This is supported by the fact that a market survey conducted by the U.S. Army Center for Health Promotion and Preventive Medicine (now known as U.S. Army Public Health Command) found that commercial off-the-shelf (COTS) recreational water purification products do not provide a true "scoop and go" approach for portable water purification (i.e. a hands-free device that can purify surface water away from the water source) and they also fail several critical mission requirements (e.g. size, weight, flow rates, efficacy against a wide range of contaminants that may be encountered on the battlefield, ease of use).

Prior to the fielding of the IWPS kit by the Marine Corps in 2006, that was developed by Cascade Designs, the Marine Corps' approach for treating water at the individual warfighter level was primarily the use of chemical disinfectants, in particular Portable Aqua iodine tablets or Chlor-Floc tablets (sodium dichloroisocyanurate as the disinfectant with aluminum sulfate as a flocculating agent). The advantage of these chemical disinfectants is that they can be easily and quickly added to the hydration reservoir or canteen as it is filled at the surface water source. However, all chemical disinfectants are unable to remove chlorine resistant protozoa (e.g. cryptosporidium) without a dwell time of 4 hours of longer. These long disinfection times put the warfighter at risk from becoming dehydrated on the battlefield. Furthermore, the effectiveness of these chemical disinfectants (including halogenated resins) is highly dependent on the concentration of organic carbon arising from natural organic matter (NOM) and the temperature of the surface water. Additionally, the halogen based disinfectants decrease the palatability of the treated water (affects both tastes and odor) which has been shown to reduce the water intake of the warfighter.

Cascade Designs was the Lead Systems Integrator on a Phase III SBIR project, co-funded by MARCOSYSCOM, to develop a modular in-line water purification system that addresses the many limitations associated with using chemical disinfectants for purifying water on the battlefield. The project team at Cascade Designs came to the conclusion that the optimal water purification system for removing the broadest possible spectrum of waterborne contaminants encountered on the battlefield would utilize a combination of chemical disinfection, size exclusion filtration and adsorptive media. It was this design philosophy that was the basis of the IWPS kit that was developed under this SBIR program and subsequently commercialized by Cascade Designs. The IWPS kit approach is based on a two stage process to remove all microbiological pathogens from a contaminated water source (see Figure 1). The contaminated water stored in the warfighter's 3 L tactical hydration reservoir is first treated with a chemical oxidant to remove any viruses and bacteria that may be present in the untreated water (e.g. using chlorine tablets, iodine tablets or MSR MIOX Purifier). The chemically treated water then flows through the MSR IWPS in-line filter which is mounted on the drink tube. The MSR IWPS in-line filter is comprised of a 0.2 μm hollow fiber MF membrane (removes protozoa, bacteria, suspended solids and colloidal particles by a size exclusion mechanism) followed by a packed bed of granular activated carbon (improves the palatability of the water by removing the residual halogenated oxidant and dissolved organic contaminants).

Figure 1. Photographs of the current IWPS water purification kit being fielded by the Marine Corps.

The major advantages of this approach was that it reduced the dwell time from 4 hours to 10 minutes before the water was microbiologically safe to consume, and the palatability of the water was greatly improved since the granular activated carbon packed bed eliminated the chlorinated taste of the filtered water. The filtered water is also more visually appealing since the physical barrier nature of the MF membrane removes suspended solids and colloidal particles from the surface water. Independent testing performed by BioVir Laboratories demonstrated that the MSR IWPS in-line filter successfully passed the microbiological removal requirements of NSF Protocol P248 with a filter capacity in excess of 300 L if the water had first been pre-treated with a chemical oxidant (e.g. oxidant produced by the MSR MIOX Purifier) to remove viruses with a 10 minute dwell time. As a result of the improved water quality that is achieved by the MSR IWPS in-line filters, over 250,000 in-line filters have been fielded by the Marine Corps.

<u>Innovative Filter Design for a Microbiological Purifier</u>

Despite all of the performance advantages in water purification gained by replacing the “chemical oxidants only” approach with the IWPS kit developed by Cascade Designs, this combined chemical disinfection/in-line filtration approach has several limitations that inhibit its widespread implementation. The performance limitations of the MSR IWPS in-line filter are strongly related to the properties of the hollow fiber microfiltration membrane:

- The pore size of the MF hollow fiber membrane (0.2 μm) is larger than virus particles (0.02-0.05 μm) and therefore any viruses present in the contaminated water source must be first removed by a chemical disinfectant. (i.e. system is not a hands-free device).
- The hollow fiber membrane makes the filter prone to freeze/thaw damage after it has been used in the field.
- The poor mechanical durability of the hollow fiber membrane requires the use of a heavy ABS filter housing in order to achieve a ruggedized system design.

Finally, the rigid form factor of the MSR IWPS in-line filter makes it less than ideal from an ergonomic perspective when mounted inside an ILBE compatible hydration carrier. This ergonomic issue would also be encountered if the water purification membrane was either a classic pleated flat sheet or ceramic membrane.

To address the Marine Corps' need for an improved water purification system at the individual warfighter level, Cascade Designs is proposing a highly innovative design that is based on having the filter placed inside the tactical 3 L hydration reservoir rather than the conventional approach of having the filter mounted on the drink tube between the hydration reservoir and the bite valve. Mounting the filter inside the 3 L hydration reservoir directs that the ideal form factor for the proposed filter is a flexible rectangular filter that is only a few tenths of an inch thick. The lack of an external filter component will reduce the lost water volume caused by displacement from the filter being inside the external carrier and it will eliminate any risk of the filter kinking the drinking tube.

Our envisaged design of the flat filter is based on a multiple layer approach, which will prevent the performance of the filter from being impeded when treating water with high turbidity, enable a broad spectrum of chemical contaminants to be removed, maximize the mechanical durability of the filter, and to allow the filter to be safely handled in the field without damaging the membrane (Figure 2). Based on the dimensions of the current ILBE 3 L hydration reservoir fabricated by Source (7.25 x 18.25 inches), it was anticipated that the maximum size of the filter that can be readily inserted into the hydration bladder is (6.5 x 15 x 0.3 inches). This would have equated to a membrane surface of 0.12 m^2 which is similar in the effective membrane surface area to the MF hollow fiber membrane that is potted into our MSR IWPS in-line filter (0.15 m^2). However, the beta prototype produced has significantly lower available surface area (0.0568 m^2) as the handmade manufacturing process led to the need for a larger bonding area.

Figure 2. Beta prototypes of flat filter A) Nylon based microfiltration filter B) PES based microfiltration filter C) PES based ultrafiltration filter

The filter will remain fully wetted in the hydration bag as the hydration bag wall collapses around the filter while the bag is emptying. A separation layer on the outside of the filter will allow water contact to the entire surface of the filter, preventing the bladder from sealing off parts of the membrane even as the bag is nearly empty.

2 Breadboard Development Effort

Following selection of the most promising materials, a series of studies were performed to examine the performance of these and evaluate them as part of a breadboard system. This approach allows for a first look at the capabilities of the chosen materials as part of a system, as well as beginning the process of developing fabrication techniques, which will be built on in subsequent tasks.

2.1 Task 1.1: Membrane Sourcing and Characterization According to the NSF P248 Protocol

Cascade Designs initially surveyed many different commercially available flat sheet membranes, from our network of potential suppliers, for their flow characteristics and efficacy in removing microbiological contaminants. This included literature based evaluations of products from General Electric (GE), Maine Manufacturing, Sepro Membranes, Microdyne-Nadir, Pall Corp., Koch, and KX Technologies as well as membrane distributors like Sterlitech. This approach of examining available literature on different materials allowed CDI to significantly reduce the testing burden of this project by narrowing down the number of samples that warranted testing at our facility. However, it was critical that sheet materials were tested in order to validate claims and guide decisions as to appropriateness of use in our novel filter design. One example of this is found in ultrafiltration (UF) membranes. Making a selection of a UF membrane based on literature is especially problematic as these membranes are rarely rated for viral reduction. Pore size claims for these membranes are often based on the rejection of a specific molecule not virus.

When filtering contaminants of this size (on the order of 0.02 µm) the chemistry and surface charge of materials plays a very significant role. The end result of this is that significant variation in efficacy and water permeability are observed between membranes even if they claim the same particle size rejection rating.

The water production of each membrane was measured at a feed pressure of 3.0 psi over a period of 10 minutes. This not only allowed for a comparison of water permeability but also wettability. For this application it was important that the material was capable of achieving its maximum water production rate without the need for elevated pressures or addition of wetting agents. The microbiological efficacy of the flat sheet membranes were measured based on the procedures outlined in the NSF P248 protocol at a feed pressure of 3.0 psi. Experiments involved testing the membranes using Type I and Type II/III water. In this way all candidate materials were examined against the requirements for a microbiological purifier (i.e. > 4 log reduction of viruses; > 6 log reduction of bacteria). All of the experimental data including: viral removal efficacy (expressed as a log reduction), pure water permeability of the membrane (LMH/psi) at a feed pressure of 3.0 psi, and whether the membrane needed to be primed was then used for comparison.

Tables 1 and 2, below, display the results of the better performing membranes tested during this phase of the project. In order to ensure that all generated data could be compared in an "apples-to-apples" scenario, a standardized size of 20.25 in^2 was used for these evaluations. None of the membranes tested showed significant advantages or disadvantages in wettability. The viral efficacy evaluations found that none of the commercially available flat sheet UF membranes were capable of meeting both viral efficacy and water permeability targets. It was estimated, at this stage, that in order to meet the desired capacity of 300L, in accordance with NSF P248, while maintaining a flow rate of greater than 200mL/min, any membrane would need to possess a permeability rating of greater than 100 LMH/psi. A total of 10 different UF membranes were tested at CDI, the six (6) that showed viral efficacy are exhibited in Table 1. In reviewing the results of experimentation it was decided that Pall Corp's 100 kDa PES membrane was the closest and thus it was selected for continuation to alpha prototyping. The 3.98 LRV shown in Table 1 is the average of numerous trials, many of which indicated a greater than 4 log reduction. For this reason, it was suspected that the observed efficacy was a result of the small sample nature of the material used in these evaluations

Table 1. Ultrafiltration membrane efficacy and water permeability performance. Each membrane tested removed all bacteria from both challenge waters types.

Membrane Supplier	Pore Size (µm or kDa)	Membrane Material	Water Permeability (LMH/psi)	Virus Removal (Log Reduction)
GE	0.03 µm	PES	256	1.39
Sterlitech	100 kDa	PVDF	52	2.64
Nadir	0.05 µm	PES	56	3.01
Sepro	75 kDa	PVDF	537	1.44
Sepro	20 kDa	PAN	38	3.97
PALL	100 kDa	PES	95	3.98

Although the use of a microfiltration (MF) membrane alone does not fully satisfy the requirements of NSF P248 for microbiological efficacy (does not achieve > 4.0 log reduction of virus) it was still evaluated as an option for the following reasons:

- The addition of an adsorptive media downstream of a MF membrane may provide the needed viral efficacy;
- It is possible to improve on the current IWPS kit (MF membrane and oxidant) by adding the benefits of the flat filter design even if the membrane is not providing viral efficacy
- It mitigates the risk of the water production rate and capacity that could be achieved by the UF membranes

Twenty-five (25) different MF membranes were tested at CDI. Of these, the eight top performing samples, in terms of flow and efficacy, are shown in Table 2. During experimentation with these products it became clear that in addition to flow and efficacy, durability would also be an important quality to evaluate. It was found that even if a given membrane possessed high water permeability and maintained the required greater than 6 log reduction of bacteria it could potentially be too fragile for this particular application. The [redacted] (b) (4) [redacted] was selected as it attained the highest flow rates of any evaluated membrane and still maintained greater than 6 log bacterial reduction; however, this membrane is thin, which raised some concerns about its resistance to damage over time. In order to mitigate this, a nylon based 0.2 µm membrane produced by Maine Manufacturing was also selected, as it was found to have acceptable performance while also being the most durable or rugged membrane of all of the samples tested.

Table 2. Microfiltration membrane efficacy and water permeability performance.

Membrane Supplier	Pore Size (µm)	Membrane Material	Water Permeability (LMH/psi)	Bacteria Removal (Log Reduction)	Virus Removal (Log Reduction)
PALL	0.2	PES	1461	7.54	0.59
Millipore	0.2	PVDF	127	7.51	
Millipore	0.1	PVDF	52	7.51	
Nadir	0.2	PVDF	147	3.56	
Pall	0.2	PES	805	7.51	0.20
Pall	0.1	PES	169	6.23	
Maine Mfg.	0.2	Nylon	531	7.46	0.17
Sterlitech	0.1	PES	272	6.66	0.89

2.2 Task 1.2: Sourcing and Characterization of other Filter Components

This task was aimed at the development of the other materials that were required to fabricate the flat filter. Specifically, this included the selection of materials for three components: the elements to provide the structural support to the filter; the pre-filter for removing turbid matter that would likely foul the purification membrane, from the water; and the carbon sheet for improving the palatability of the treated water. Literature on adsorbent materials for chemical removal and taste/odor improvement was also researched through Carbon Filter Technology, KX Technologies, MAST Carbon, Mead Westvaco, Calgon Carbon Corp., Ahlstrom and others. Finally, materials for construction of the filter including separation layer options, different bonding products (e.g. adhesives, tie layers), and pre-filter options (e.g. 5 micron felt, etc.) were searched out. Cascade Designs used their network of suppliers to obtain samples of these filter components to investigate their performance with respect to their use in the proposed flat filter design. Cascade Designs only obtained materials that have already been approved by the FDA or NSF for use in drinking water applications.

With respect to the structural support, different openings and mesh thicknesses of the plastic scrim were examined to determine how effective they were at removing large suspended solids without impeding water transport into the pre-filter layer. Different fine mesh, woven and non-woven materials were explored as candidate materials for the pre-filter which helps resist pre-mature fouling of the water purification membrane due to exposure to turbidity. However, it was quickly determined that the applicability of these components could not be rigorously tested until they could be incorporated into alpha prototypes, where their ability to allow maintenance of flow under pressure could be more readily evaluated.

Porous carbon sheets were investigated to determine their effectiveness at removing dissolved organics and any residual oxidants that might be present in the feed water. Carbon filtration samples were procured from the following suppliers:

- CHEMVIRON: activated carbon cloth.
- KX TECHNOLOGIES: carbon sheets, corrugated filters.
- MAST CARBON SUPPORT (UK): carbon felt, carbon cloth
- MEAD WESTVACO: cellulosic substrates.
- CARBON FILTER TECHNOLOGY: carbon sheet substrates.

In order to down select the best candidates for use in the next stages of development, each material was evaluated for permeability as well as chemical removal kinetics. This testing was performed using a 0.0017 m^2 sample of material in a circular housing. Figure 3 shows the result of the permeability evaluations where the pressure drop required to maintain flow rates of 200, 400, 1000, and 1200 mL/min were measured and graphed. Testing indicated that pressure drop was not likely to be an issue for any of the tested materials.

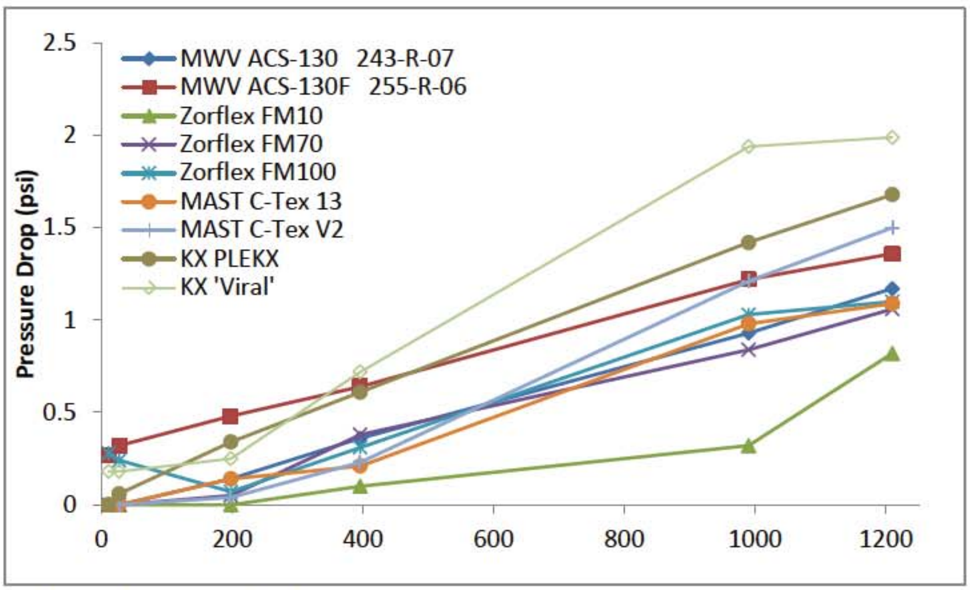

Figure 3. Carbon sheet materials flow vs. pressure comparison

As the permeability performance of all the different materials was acceptable it became necessary to rely on chemical reduction efficacy for down selection. However, given the large number of materials to evaluate, it was decided that at this stage chlorine removal kinetics and iodine capacity would be used for an initial comparison. The results of this testing are shown in Figures 4 and 5. It is critical to note that some of the material's (e.g. MAST C-Tex V2 and KX 'Viral') kinetics were so impressive that it became necessary to use higher concentrations of influent in order to more appropriately evaluate them.

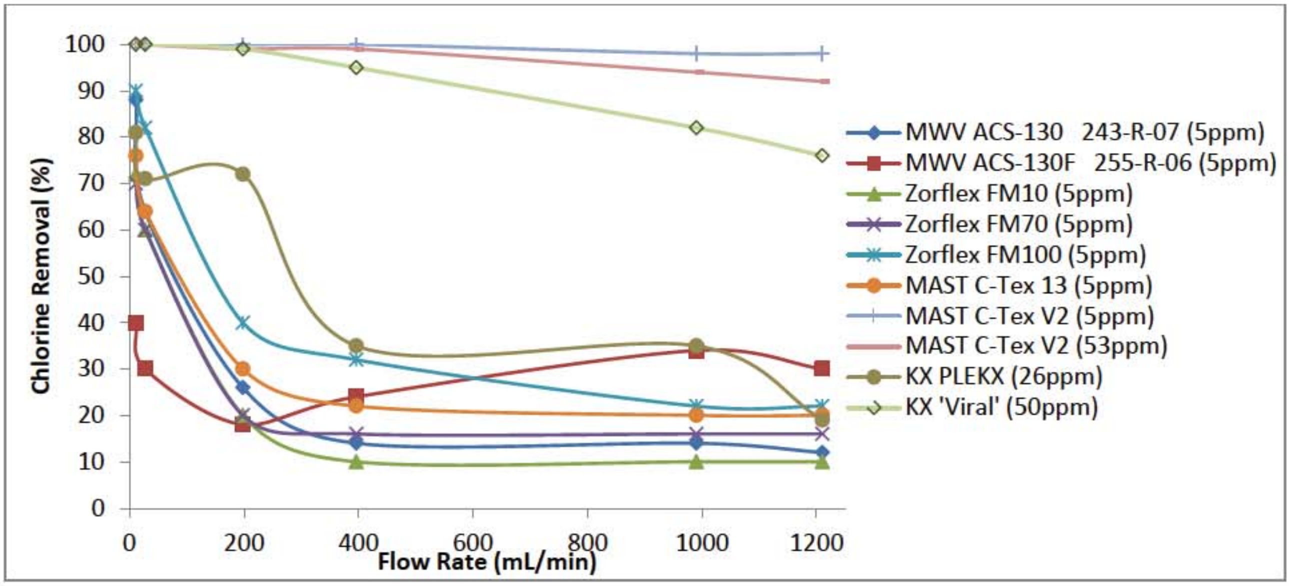

Figure 4. Chlorine removal kinetics of 0.0017 m^2 pieces of various carbon based sheet materials. Note that the legend denotes different influent concentrations used in some cases.

The initial 5 ppm free available chlorine challenge was successfully completed so rapidly by the MAST C-Tex V2, KX 'Viral', and KX PLEKX materials that it was necessary to increase the challenge concentration in order to differentiate between them. Of these three materials it was found that the MAST C-Tex V2 was the best performing for chlorine reduction with greater than 90% of the 53 ppm influent being removed even at a flow rate of 1,200 mL/min.

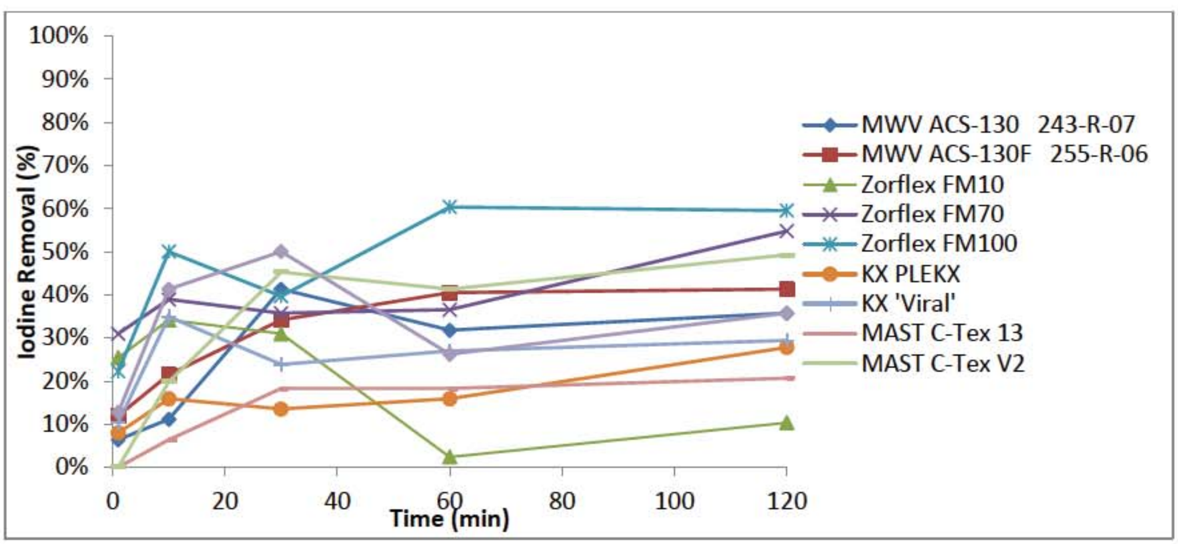

Figure 5. Iodine capacity of 0.0101 m^2 pieces of various carbon based sheet materials. An influent challenge of 12.6 g/L Iodine was used to measure % removal over a period of 2 hrs (120 min).

In order to take a first look at the capacity of each material a 0.0101 m^2 piece of each was allowed to soak in a solution of 12.6 g/L iodine for 120 minutes (2 hours) with constant stirring. The concentration remaining in the supernatant liquid was measured after 10, 30, 60, and 120 minutes of contact time. Figure 5 indicates that two of the Zorflex materials (FM70 @ 55% and FM100 @ 60%) had the highest total capacity with the MAST C-Tex V2 being a close third with 49% removal. [redacted] (b) (4) [redacted].

Two adsorbent sheet materials were also evaluated for their ability to remove microbes in accordance with NSF P248. These materials included [redacted] (b) (4) [redacted] achieving greater than 6 log bacteria and greater than 4 log virus removal while maintaining acceptable flow characteristics; However, their efficacy did not carry through to General Test Water 2 (GTW2) as it was found that none of these materials achieved the required greater than 4 log reduction of virus for more than 1 liter. For this reason it was decided to focus on the combination of a membrane rejection layer for microbial efficacy, and a carbon sheet material for broad range chemical removal.

2.3 Task 1.3: Assembly and Testing of the Breadboard System

Based on the information that was obtained in Tasks 1.1 and 1.2, Cascade Designs revisited the conceptual design of the proposed flat filter. Considering the performance of the materials tested it was decided that the final design would be comprised of a membrane rejection layer for microbiological removal, a carbon sheet material for broad range chemical removal, and a separation material to ensure maintenance of flow under pressure. Having settled upon a design for the breadboard filter, Cascade Designs used this task to explore different assembly techniques to fabricate the filter as well as evaluating the different layers for capacity and clean-ability before moving to alpha prototyping.

Exploration of Different Fabrication Methods:

Due to its multiple layer construction, a new commercially viable fabrication approach would be required for producing this filter. However, it was possible to leverage some of the processing techniques used to fabricate spiral wound membrane elements. Cascade Designs explored the effectiveness of different assembly techniques such as adhesive bonding and thermal bonding, to fabricate the breadboard filter.

(b) (4) [redacted]

(b) (4)
[redacted]

Table 3. Series of initial thermal bonding trials.

(b) (4)
[redacted]

(b) (4)
[redacted]

Testing of the nylon membrane, which was far more resistant to heat, showed that it was impossible to create a strong bond without causing heat damage to the membrane. Following this discovery, testing was performed with the advent of bonding films. These thin, relatively low melt films are designed to create a tie layer between two otherwise difficult to bond materials. [redacted] (b) (4)

The UF membranes also proved to be more problematic during thermal welding. Numerous experiments, including viral and permeability testing of welded UF sheet materials, were performed. A strong bond was formed both with and without the incorporation of polyurethane bonding film; however, evaluations of the bonded membranes showed that without bonding film, the temperature required to create a strong bond also resulted in constriction of membrane pores and significantly reduced permeability (i.e. 50% reduction in water production at 3 psi). The incorporation of bonding film allowed for reduced bonding temperature, consequently avoiding pore narrowing but, upon evaluating these samples, it was found that the pores were apparently being enlarged which resulted in lower viral efficacy (i.e. 2 LRV instead of the desired 4 LRV).

Having exhausted feasible options for thermal bonding, the next approach explored was the use of liquid adhesives. After several trials an adequate option was found for experimentation purposes; however it was discovered to be currently unapproved for drinking water contact. Additionally, this approach would not be conducive to production scale manufacturing. As such, some work is still needed in this area to develop an appropriate means of bonding flat sheet UF membranes. In order to avoid delaying the project, it was decided to continue to explore options to this end while continuing development using the unapproved adhesive.

Evaluation of Materials for Capacity and Clean-ability:

Following down selection to the most promising microbial removal membranes, testing of these remaining selected materials was performed in order to evaluate the feasibility of achieving the target 300L capacity as in accordance with NSF P248. Included in this experimentation were some trials of different cleaning methods, measuring the recovery achieved by each method as well as examining their applicability to a field use scenario. [redacted] (b) (4)

One major difference between this testing and the original evaluations performed during down selection was that the scale was increased from 1/30th to 1/6th. This allowed for more accurate extrapolation of flow rate production and volume treated at full scale. This change was made possible through the fabrication of a new test chamber which replaced the standard 47mm diameter housing used during initial investigations (Figure 6).

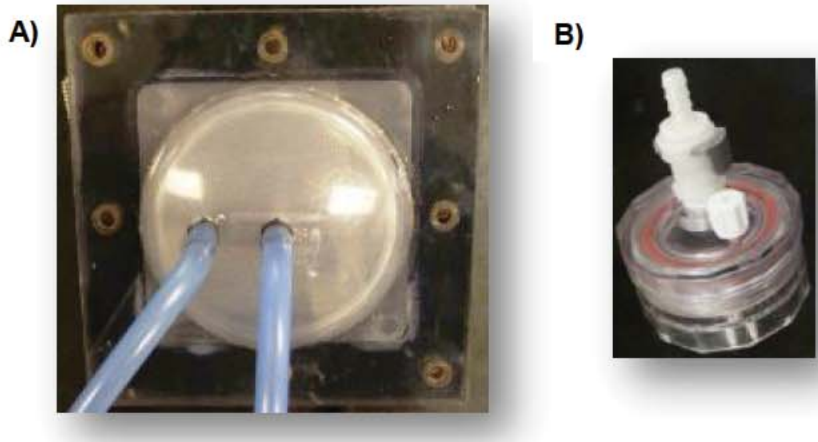

Figure 6. A) Newly fabricated 1/6th scale test fixture and B) Standard 47mm diameter test fixture.

These capacity evaluations involved an initial characterization of the membrane, including flow and pressure in deionized water as well as a small volume bacterial challenge to confirm that all seals were effectively in place. Once confirmation that the membrane was correctly installed was attained, NSF P248 General Test Water 2 (GTW2) was applied with a feed pressure of 3psi to replicate that which could be achieved by a warfighter. An inline pressure gauge was installed in order to allow for the pressure to be held constant while monitoring the change in flow rate over the volume treated.

Plotting the change in water permeability of the system over time allows for an evaluation of the expected performance when built into a full scale device. This test showed that the PALL SUPOR 200 MF membrane is capable of treating 196 liters of GTW2 without any cleaning (34.5L in the scaled down device; Figure 7). This is more than enough capacity as the 300L target capacity consists of 150L of GTW1 and 150L of GTW2. Testing using GTW1 has shown no significant change in flow over the targeted 150L volume. It is also important to note that the initial flow rate observed in this test was 0.415 L/min which when adjusted to a full scale device would coincide with a water production rate of 2.36 L/min which is significantly higher than the current IWPS (~1.2 L/min). It is important to note that this water production will be reduced upon the addition of other filter components (e.g. drink tube, carbon sheet). However, it is not anticipated that these will have a large impact as each of them has exhibited exceptionally high flow at a feed pressure of 3psi.

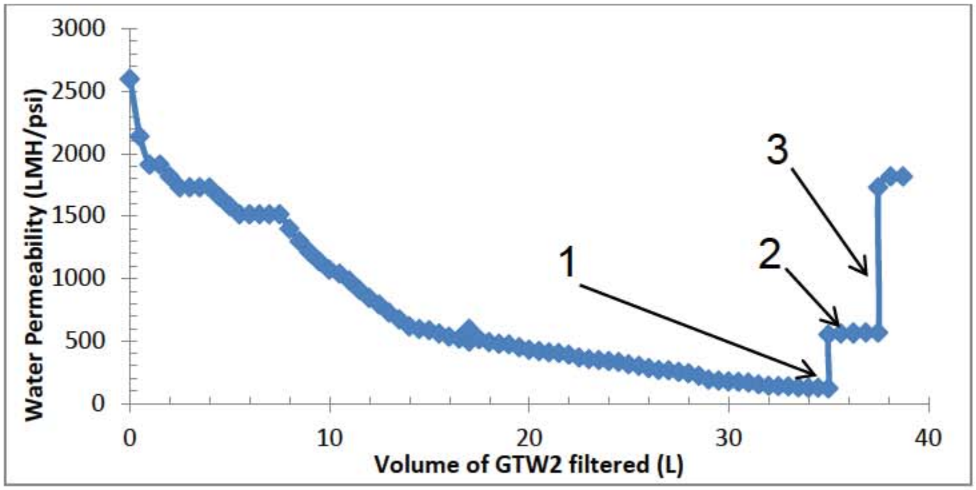

Figure 7. Water permeability decay of 0.01m^2 of PALL SUPOR 200 MF membrane when treating NSF P248 GTW2; Cleaning Methods 1)Back flush at 125 mL/min for 200mL 2)Shake test fixture to free dirt and drain 3)Open and swab membrane surface

Figure 7 also shows the results of the initial exploration of different cleaning methods. The traditional method, employed by the current IWPS system, is to perform a back-flush of the system once the flow rate drops to an unacceptable level. This is very simple to perform in the field and provides a valuable increase in capacity. In this test it was found that a 21% recovery of the original water permeability was achieved. The second cleaning method explored was called "shake cleaning". The development team at Cascade Designs hypothesized that the transition to a flat sheet membrane would allow the debris collected on the surface to be dislodged with a simple sloshing or shaking of the hydration bladder followed by dumping the wash water out of the reservoir and refilling it.

In practice it was found that this approach provided very minimal recovery of flow however, it is possible that it could be more effective once a pre-filter is in place. The placement of a pre-filter will do two things to aid this cleaning method. First, it will remove larger particles reducing the fouling rate of the membrane in general. Second, the pre-filter will be in direct contact with the 'dirty' side of the membrane such that, when shaking to remove collected debris, it will rub against the membrane freeing sediment and other fouling material. This was evaluated further during the alpha prototyping stage where all components were combine into a single filter.

The third cleaning method evaluated here was the use of a "swab cleaning". One of the major advantages of utilizing flat sheet technologies is the increase in accessibility to the active surface of the material. In the current IWPS uses a 0.2 micron hollow fiber membrane to achieve the desired bacteria and protozoa removal. The advantage of hollow fiber is that it provides a very high surface area in a small volume however; this bundling of small fibers prevents access to the surface of the membrane there by reducing the cleaning options. The open flat sheet design of the proposed filter allows the warfighter to reach into the bag and wipe away collected debris refreshing the active surface area. Using this method on the heavily used membrane resulted in a 70% recovery.

The next step in the breadboard device evaluation was to consider the combination of the different layers to be used and decide if the feasibility of achieving the expressed goals was high enough to move forward into alpha prototype development. In examining the testing that had been performed it was clear that the primary flow restriction would come from the membranes as both the MF (330-900 LMH/psi) and UF (35-65 LMH/psi) membranes have the lowest permeability of any of the components to be included. Given that the MF membranes both surpassed the desired 150L capacity of GTW2, albeit in a scaled down test, the feasibility of achieving the desired targets with a microfiltration membrane is very high.

The UF membranes have relatively low permeability and previous testing indicates that achieving the desired 150L capacity of GTW2 will rely on the effectiveness of the cleaning methods used to extend filter life. However even with the exceptional recovery achieved by the 'swab cleaning' it is unlikely that a full 300L NSF P248 capacity will be achieved with an ultrafiltration. This was discussed with the larger development team including representatives from ONR before transitioning to alpha prototyping. It was collectively decided at this point that development of both MF and UF prototypes would continue in order to see how far the UF technology could be taken within the limits of this project.

3 Alpha Prototype Development

3.1 Task 2.1: Fabrication of the Alpha Prototype Filter and Characterization According to the NSF P248 Protocol

Based on all of the performance data obtained in Task 1, Cascade Designs used their in-house design expertise to produce drawings to illustrate our different conceptual designs of the alpha prototype filter. These models, and associated performance expectations based on the breadboard device evaluations, were then presented to representatives of ONR for review. The two different designs included "two compartment" and "bag within a bag" approaches. The two compartment approach places the filtration sheets in the center of the hydration reservoir where they are welded into the bag, separating it into two separate compartments or sides. The source water is collected through the wide mouth opening as usual and then it passes through the filtration layer to the other side of the reservoir where the drink tube attaches. The advantage of this approach is that it is simplifies production with all of the layers being the same size reducing the need for customized tooling. However, this design has only about half the surface area of the "bag within a bag" and necessitates that the filter be built into the hydration reservoir during manufacturing.

The "bag within a bag" design allows the water to surround the filter on all sides, almost doubling the available surface area. It is also possible that this design would allow the filter to be more readily incorporated into existing hydration reservoirs. The challenges associated with employing this approach include the increased need for customized tooling, multiple weld joints, and drink tube attachment port installation. The need for additional tooling is derived from the fact that the filter must be smaller than the hydration reservoir in order to fit inside the reservoir. Additionally, if the increased surface area is to be gained at each layer, then each material will have to fit inside the previous one creating the need for a different bonding tool for each media used. This, in turn, leads to multiple weld joints within the final filter increasing the overall complexity. The final challenge is the attachment of the drink tube which will have to draw water from the inner most chamber of the filter out through the dirty water reservoir to the drink tube. This makes seals absolutely critical to success as any failures would result in source water contaminating the treated water.

After reviewing these designs it was decided that the increased flow rate, capacity, and possible integration with existing reservoirs made the "bag within a bag" approach more favorable despite its challenges. Using the down-selected design for the alpha prototype, Cascade Designs considered the material options down selected during Task 1 which included: 2 microfiltration membranes, 2 ultrafiltration membranes, 3 chemical removal layers, and over 40 different materials for internal construction. Testing the resulting prototype options (there are over 480 of them) was not a feasible task so as many as possible were eliminated through the data that had been generated. The numerous internal structure options were then evaluated using PALL SUPOR 200 microfiltration membrane as any relative differences in permeability should translate well regardless of the membrane selected.

Activated Carbon Sheet

Thin Plastic Layers

Dropstitch Material w/ Padded Taper on Top

Carbon Sheet w/ Fiber Pad

Figure 8. Some of the internal construction materials considered during alpha prototype development

Figure 9. Series of alpha prototypes constructed for evaluation of internal construction's effect on filter permeability. They possess a surface area of 0.0104m^2 (~1/5th scale).

To this end, a series of different alpha prototypes were fabricated (Figure 9), each with different internal structure. Once completed, these were tested for bacterial removal to ensure that the integrity of each was confirmed before measuring water permeability. Table 4 displays the range of different permeability measurements that taken during these evaluations. Not all of the options that were tested are listed, however the lowest permeability option (i.e. fully rigid plastic @ 284 LMH/psi) and the five highest performance are shown.

Table 4. Range of different permeability's achieved during evaluation of alternate internal structure options including the top five observed [Not all tested options are listed here].

Option #	Alpha Prototypes Made with Microfiltration Membrane	Permeability (LMH/PSI @ 3 psi)
1	Fully Rigid Plastic (Housing and Internals)	284
2	2mm Thick Felt	707
3	2mm Thick Felt|Plastic Screen x2|2mm Thick Felt	848
4	4.2 mm Thick Natural Pad	1101
5	1 Layer Thin Plastic (#2) + Padded Taper	1162
6	2 Layers Thin Plastic (#1) + Padded Taper	1292
7	4.76 mm Thick Semi-Rigid Pad	1351
8	Drop Stitch Mesh – 2	1377
9	Drop Stitch Mesh - 1	1400
10	Drop Stitch Mesh - 3	1458
11	Carbon Sheet|Drop Stitch Mesh|Carbon Sheet	1492
12	Thin Plastic #1|Thin Plastic #2 (x2)|Thin Plastic #1	1494
13	Drop Stitch Mesh + Padded Taper + Open Netting	1521
14	4.5 mm Thick Soft Pad + Padded Taper + Open Netting	1531
15	Thin Plastic #1|Carbon Sheet|Thin Plastic #2 (x2)|Carbon Sheet|Thin Plastic #1	1531

In order to further analyze the best performing internal structure options, the top four were fabricated into new alpha prototypes and tested for capacity in NSF P248 GTW2. This highly contaminated water (> 30 NTU, > 10mg/L TOC, etc.) was also inoculated with the challenge level concentration of bacteria (> 10^7 cfu/100mL) for the entire test volume in order to provide an absolute worst case scenario (see Figure 10). Although both option 13 and option 12 failed to achieve the desired 30 liters of GTW2 (150L GTW2 at full scale to meet 300L total capacity goal), option 12 was not eliminated from consideration. It was decided to continue evaluating the combination of multiple layers of different patterned thin plastic screens for two reasons.

First, it provides the thinnest profile filter of all the options considered which is preferable from an ergonomic stand point once installed. Second, it was observed during testing that, due to the thin nature of this structure, the membrane was actually being pull down such that it covered most of the outlet port on the alpha prototype thereby significantly increasing the flow restriction at that point. It was theorized that extending the length of the screen material, such that it sandwiched the outlet port, would solve this issue and result in more favorable flow and capacity.

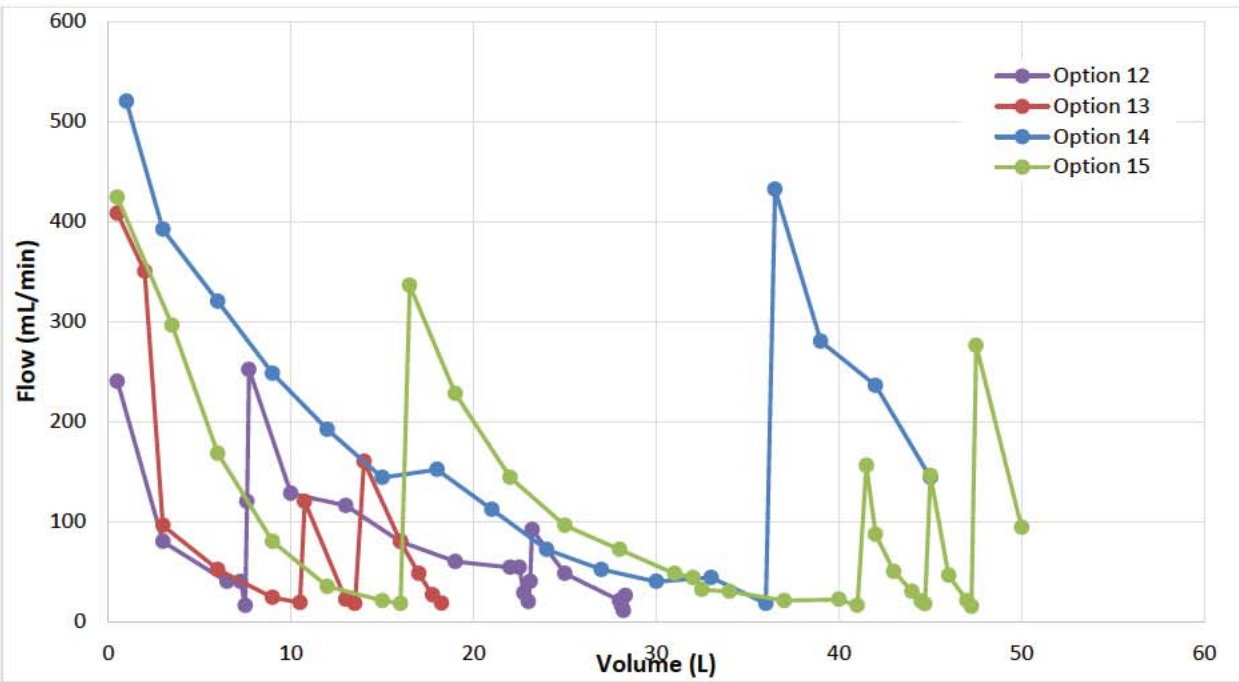

Figure 10. NSF GTW2 capacity (with full challenge level microorganisms) of top four internal structure options fabricated into a 1/5th scale (0.0104m^2) alpha prototype using PALL SUPOR 200 microfiltration membrane. Detailed descriptions of options are listed in Table 4.

Therefore, three of the four internal structure designs which were tested demonstrated great promise for functioning as microbiologically effective and meeting the 300 L filter capacity requirement. Figure 10 also shows several points of significant recovery from cleaning the alpha prototype. These cleanings were followed the same "swab cleaning" method described above were the surface of the prototype was wiped and quickly rinsed in a reservoir before continuing. The average recovery observed across all 4 of the different internal structure options was measured to be ~80% of the original flow rate. This is a significant improvement over the 20-

30% recovery of backflushing the current IWPS and is also an increase over the 70% recovery that was observed during breadboard evaluations.

With this information it was anticipated that all of the microfiltration alpha prototype filters fabricated would meet the flow, microbiological efficacy and filter capacity requirements. However, one additional test was performed where internal structure option 12 (as a worst case) was used in combination with the nylon microfiltration membrane produced by Maine Manufacturing in order to validate this projection. The nylon based alpha prototype also exhibited the restriction of flow previously observed at the outlet port with this internal structure configuration. However, the nylon prototype did successfully treat greater than 40 liters of NSF P248 GTW2 (Figure 11) without any cleaning while maintaining a flow rate of greater than 40 mL/min (222 mL/min at full scale). This testing indicates that, although the nylon membrane possess a lower permeability than the PES material (531 LMH/psi vs. 1461 LMH/psi) it is still a viable option.

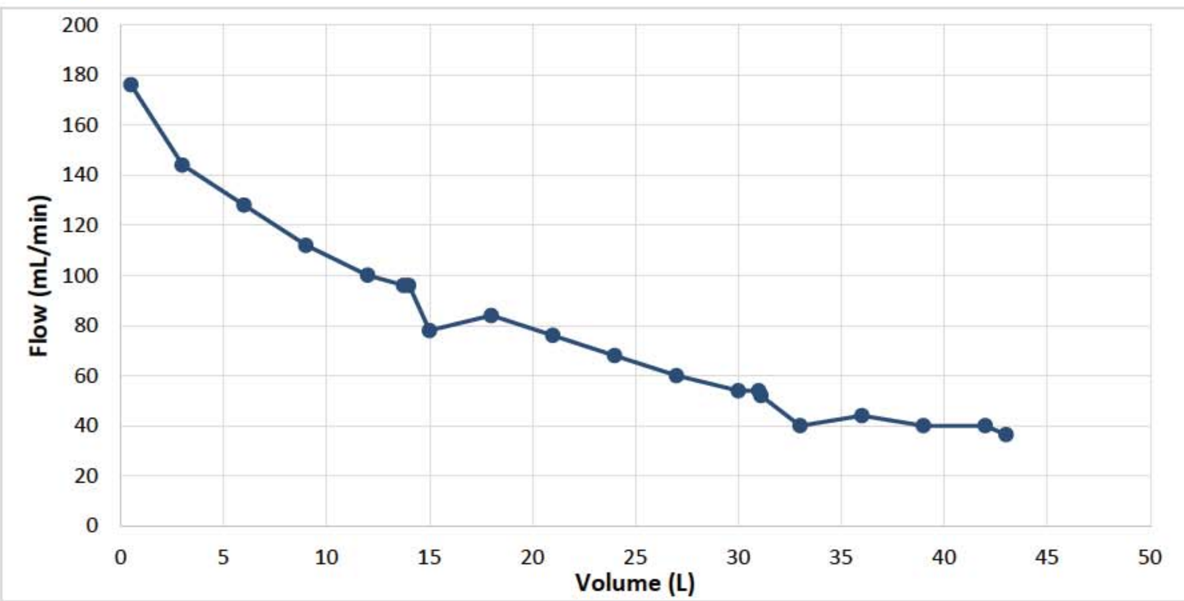

Figure 11. Evaluation of NSF P248 GTW2 capacity (with full challenge microorganisms) of an alpha prototype (1/5th scale) constructed with Option 12 internal structure and the selected nylon microfiltration membrane.

It is also important to note that at no point during these evaluations did the bacterial log reduction fall below the desired greater than 6 log reduction. There were, however, several lessons learned about the construction of the prototypes. Bonding the membranes with the internal structures in place adds complexity to the tool required as they tend to misalign unless compressed and held in place. Additional development was done during beta prototyping in the area of manufacturing processes as the current methods are not production ready or cost effective.

Pre-filtration Development

The last piece of filter development that was explored during alpha prototyping was the different options for pre-filtration. CDI's development of several outdoor water treatment products has shown that the addition of a pre-filtration step can both extend filter life and protect the microbial reject layer from damaging debris. Given the desire to keep the filter as simple as possible for the user, the three approaches to pre-filtration tested were all based on the addition of an outer layer. This adds no extra steps and very little size/weight. Each of these pre-filter options are being tested for their ability to reduce fouling. These materials include:

- A 5 micron felt material - capable of removing most suspended solids;
- A similar felt material comprised of activated carbon - capable of removing suspended solids as well as some organic contaminants (NOM – e.g. tannic acid) and improving taste/odor;
- A sheet material produced by KX technologies that incorporates modified PAC with a nominal pore size of 0.2 micron known as FACT® or fibrillated adsorbent cellulose technology (Figure 1).

The FACT® sheet material (Figure 12) has unique properties that make it able to not only removes NOM and suspended solids but also protozoa, bacteria, and even adsorbs some virus giving it the theoretical potential to significantly reduce the burden placed on the MF or UF flat sheet membrane in a flat filter device.

(b) (4)

[redacted]

Figure 12. A) Pleated FACT® sheet B) Scanning electron microscope pictures of KX Technologies FACT® material and *E. coli* (bacteria) trapped/lysed in it.

Experimentation conducted was aimed at evaluating the FACT® materials ability to improve the NSF P248 GTW2 capacity of a UF hollow fiber filter and determine effects it may have on initial flow rate. The decision was made to use a ultra-filtration hollow fiber (UFHF) filter instead of a flat filter prototype because the UFHF filter is in the most need of improved capacity. This approach allows for a clearer understanding and increased confidence with respect to determinations of the effect that the FACT® is having on filter performance overall. Figure 13 compares the results from this testing to findings from the same GTW2 capacity test performed on a UFHF filter without the use of FACT® as a pre-filter.

This filter (FACT® pre-filter + UFHF) was used to treat 360L of GTW1 (simulated tap water) with no measurable degradation of flow before starting the GTW2 capacity shown in Figure 13. The FACT® sheet used was full scale (0.15 m^2 – pleated) and did not appear to have any effect on the flow rate in GTW2 with both starting at ~ 550 mL/min and decaying at a very similar rate over the first 200 L of GTW2 treated. The effluent treated GTW2 water where the pre-filter was used had the appearance of tap water (clear and colorless) while the water treated without the pre-filter was significantly improved over GTW2 but still maintained a pale yellow tint as not all of the natural organic matter (NOM) is removed by the UF membrane. For this reason it was apparent that the FACT® sheet was providing the protection originally hypothesized (removal of NOM, turbidity, some bacteria) but that it was fouling at a rate that prevented this protection from resulting in any gain in flow or capacity. Therefore, to acquire more definitive data as to the level of fouling protection being provided, the pre-filter was removed once the flow rate was near the 200 mL/min minimum (252L of GTW2 processed; 612L total volume processed).

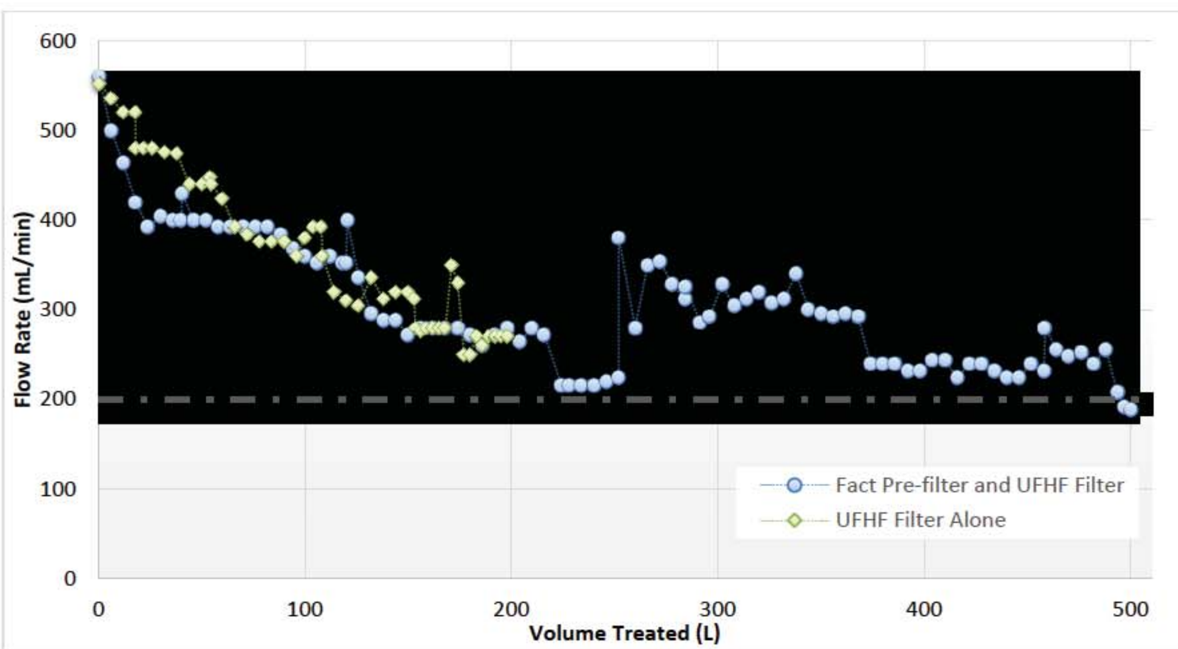

Figure 13. NSF P248 GTW2 comparison with and without FACT® Pre-filter

Once the pre-filter was removed the flow rate immediately increased from ~220 mL/min to 380 mL/min. Continued evaluation of the filter alone was performed until it no longer recovered to greater than 200 mL/min resulting in a total GTW2 capacity of 494 liters or a P248 capacity of 988 liters while maintaining all of the P248 requirements for purifier status (> 200mL/min; > 6 log bacteria reduction; > 4 log virus reduction; > 3 log protozoa reduction). When comparing this result to that of the UFHF alone it is found that the addition of the FACT® pre-filter nearly doubled the capacity if removed when flow drops to 200 mL/min. The primary disadvantage of this material is the cost and availability. As the project progressed communications with KX Technologies continued until CDI was notified that KX was not interested in providing material but only pleated cartridges. The large, round, hard plastic housing used for these cartridges remove them as an option for implementation in a flat filter device.

The next material tested was a 5 micron felt material which is currently used in the IWPS Block 1 filter. With the ability to remove some turbidity and prevent any sharp or abrasive debris from directly contacting the membrane surface, this is also the lowest cost pre-filter option. Evaluations of the two different prototypes shown in Figure 14 showed no measurable increase in P248 GTW2 capacity over similar prototypes without the pre-filter. This is thought to be due to the very fine particle size of the test dust used in GTW2 (nominally 0-5 micron) and the fact that a large part of the fouling is being caused by the NOM which is not removed by this pre-filter.

Figure 14. Removable 5 micron felt pre-filter prototypes.

Given the poor performance of the 5 micron felt and the supply issues associated with the KX material it was decided to move forward with the activated carbon based felt like material which provides the same protection and physical filtration as the 5 micron felt with the additional benefit of some organics removal and significant taste and odor improvement capabilities. These removal characteristics were well studied and are explained in the initial down selection tasks described above.

3.2 Task 2.2: Field Usability and Durability Testing of the Alpha Prototype

After demonstrating in Task 2.1 that the alpha prototype filter satisfies the flow, capacity and microbiological efficacy, Cascade Designs then undertook extensive usability and durability testing to simulate its use on the battlefield. Samples of the alpha prototype were tested by an independent review panel at Cascade Designs to examine several key usability issues which include back-flushing the filter and water production at different volumes of water within the hydration reservoir.

To determine the mechanical durability of the alpha prototype, it was dropped four times from a height of six feet onto a concrete floor. This testing is designed to assist in locating the weakest point of the filter and what steps are required to address any shortcomings on the current design of the flat filter. The freeze/thaw resistance of the alpha prototype was measured by subjecting the filter to repeated freeze thaw cycling under a variety of conditions. The filter was frozen when using several different protocols (dry, damp, submerged in water, and half submerged in water) and tested for its microbiological efficacy when thawed at room temperature. After each of these tests, the structural integrity of the filter was determined by measuring the microbiological efficacy of the alpha prototype filter according to the NSF P248 protocol using a Type I challenge water influent.

Usability Evaluations

The exploration of the effect of backflushing the flat filter prototype was designed to determine resistance to damage in the event that a user forces water and/or air back into the filter and hydration bladder. Any water reversed through filter will simply pass back through the membrane and into the hydration bladder however, any air that enters into the filter will not be able to cross the hydrophilic membrane. If the warfighter applies significant force, the lungs are capable of generating up to 3psi; this will apply pressure to the bonds of the filter. It is unrealistic to instruct warfighters to avoid inflating the filter so it is necessary to confirm that the filter is capable of withstanding this force without compromising its integrity.

In order to measure the different prototypes resistance to this type of damage three prototypes each made with one of the different membrane materials selected (PALL SUPOR 200, Maine Manufacturing Nylon, and PALL 100K Omega). Air was applied in reverse ballooning out the prototypes until a pressure of 3psi was reached. The prototype was held under water for 1 minute with observation to determine if any air was leaking. Once this was completed, each was tested for integrity using a bacterial challenge. All of the alpha prototypes passed this test.

Durability Testing

Testing the durability of the alpha prototypes was intended to provide evidence of the ability to withstand battlefield like conditions. Both drop testing and freeze/thaw resistance were evaluated through a series of experiments. It is important to note that the shape and weight of the filter will change as it moves to full scale. For this reason, only a limited number of evaluations were performed on the alpha prototypes.

Drop testing was done by dropping each of the three different alpha prototypes (three different membranes) from a height of 6 feet to concrete. The prototypes were not placed inside hydration carriers or within a hydration reservoir as not having this protection was considered the worst case scenario. Each of these was dropped three times in each of three different orientations as shown in Figure 12. Following these drops each prototype was analyzed for its ability to achieve a 6 log reduction of bacteria. It was found that all of the filter has maintained bacterial removal efficacy after all 9 drops, indicating a significant improvement in durability over the current IWPS microfilter which is rated for a 4 foot drop to concrete.

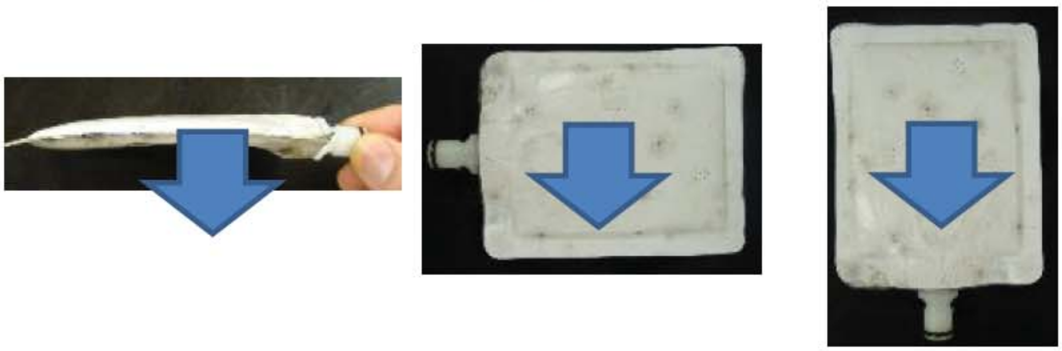

Figure 15. Orientations used for drop testing from 6 feet to concrete.

The second set of durability testing was focused on the freeze/thaw resistance of the alpha prototype. Similar to the drop testing, one prototype was made from each of the three selected membranes for this testing. Evaluations were performed by first testing each for microbial efficacy and then exposing the wetted membrane to repeated freeze/thaw cycles by holding them at -5˚C (23˚F) for 15 hours and then thawing them to room temperature. Once completely thawed each was challenged again in order to determine if microbial efficacy had been lost. Each one of these overnight freeze through microbial testing is considered a single cycle. A total of 10 cycles was completed and none of the alpha prototypes lost integrity.

As a final evaluation of alpha prototype durability some qualitative testing was done where filters were bent and curled at similar radii to what would be expected in normal use on the battlefield. This testing found that, in some cases, filters would form wrinkles which could eventually result in the development of cracks or holes especially near the drink port (Figure 16).

[redacted]

Figure 16. Damage observed during flexibility evaluations.

[redacted]

[redacted]

Figure 17. [redacted]

Although the wrinkles observed previously were not fully removed from occurrence, no damage or loss of integrity was found despite repeated flexing and bending of the prototypes. These flexibility tests were also performed on several filters after they had been used to capacity in treating GTW2 (Figure 17) and still no damage was found.

Following presentation of the findings from alpha prototype development, it was decided to proceed to beta prototype development utilizing the activated carbon sheet material for pre-filtration and implementing the use of the flexible film layer to improve durability.

4 Beta Prototype Development

4.1 Task 3.1: Design and Fabrication of the Beta Prototype Filter

The design of the beta prototype filters were based on building a full scale prototype that addressed the shortcomings of the alpha prototype filter to ensure that it meets all of the Marine Corps needs for a hands-free water purification system that is fully compatible with the ILBE hydration carrier. Using the down-selected design for the beta prototype, Cascade Designs fabricated several filters. In contrast to the alpha prototype, Cascade Designs worked on the development of low rate production techniques to assemble the beta prototype filters.

Design Options

Integration of the proposed flat filter into an ILBE compatible hydration system is critical to the success of the final design. [redacted] (b) (4)

[redacted] (b) (4)

Figure 18. [redacted] (b) (4)

(b) (4) [redacted]

After review of these two design options with representatives from ONR it was decided that development would continue with the Reservoir Integrated option (Figure 19). Three different membranes were used in fabrication including Pall Corporation's SUPOR 200 PES microfiltration membrane, Maine Manufacturing's Nylon microfiltration membrane, and Pall Corporation's 100K Omega. However, before construction began some final evaluations of the internal structure options were done to further down select between the three remaining options. These tests were performed by assembling 6 full scale beta prototypes with the Nylon membrane. Each of these was constructed with a different internal structure:

1. (b) (4) [redacted]
2. (b) (4) [redacted]
3. (b) (4) [redacted]
4. (b) (4) [redacted]
5. (b) (4) [redacted]
6. (b) (4) [redacted]

[redacted]

Figure 19. Selected Beta Prototype design.

After an initial microbial challenge to confirm their integrity, these were all tested for flow and pressure characteristics and compared based on permeability (Table 5). [redacted]

Table 5. Comparison of beta prototype filter constructed with different internal separation layers.

Option #	[redacted]	Permeability (LMH/psi)
12	[redacted]	228
12	[redacted]	518
14	[redacted]	195
14	[redacted]	377
15	[redacted]	338
15	[redacted]	528

[redacted]

(b) (4) [redacted]

(b) (4) [redacted]

(b) (4) [redacted]

Figure 20. Final Beta Prototype filter design configuration

Fabrication Development

The final step in this task was to fabricate several beta prototypes for performance testing. All of the prototypes contained the same internal structure and flexible film addition; however, several differences did exist in order to further evaluate the performance of different membranes as well as the effect of the activated carbon sheet material at full scale. (b) (4) [redacted] The one exception to this was in the fabrication of the ultrafiltration beta prototype.

[redacted] (b) (4) If the performance of this prototype is found to be promising then additional work will need to be done to source a more suitable adhesive and further develop the equipment required for more rapid production with the application of adhesives.

4.2 Task 3.2: Performance Testing of the Beta Prototype

To ensure the design of the beta prototype filter still functions as a microbiological purifier, several prototypes were tested according to the NSF P248 protocol to a capacity of 300 L. The performance benefits of the proposed filter design with respect to the current IWPS kit being fielded by the Marine Corps (mechanical durability, freeze/thaw resistance, reduction in size and weight, improved user experience) was then scientifically quantified for comparison. Upon completion of this, Cascade Designs delivered one of each of the three most promising beta prototype configurations to ONR.

Performance Evaluations

As a final step in the beta prototype development process three filters were fabricated each with a different membrane rejection layer (PALL SUPOR 200 (MF), Maine Manufacturing Nylon (MF), and PALL 100K Omega). Each of these was tested in accordance with the NSF P248 Protocol for Microbiological Purifiers in order to allow for direct comparison to be taken between the different configurations as well as to the current IWPS Microfilter. The prototypes were evaluated for capacity, flow rate, and efficacy as well as some examination of taste/odor/color improvement capabilities.

A complete summary of the results of these evaluations is provided in Table 6. The beta prototypes were found to improve upon the current IWPS system in the areas of flow rate, capacity, chemical removal, and durability. [redacted] (b) (4)

[redacted] (b) (4)

Table 6. Comparison of the performance of the UF and MF Flat-Filter Beta Prototypes to the current IWPS Microfilter.

Performance Specification	UF Flat-Filter	MF Flat-Filter	IWPS Microfilter
Protozoa - *Giardia* - *Cryptosporidium*	Yes	Yes	Yes
Bacteria - *E. coli* - *Salmonella*	Yes	Yes	Yes
Virus - *rotavirus* - *Polio*	Yes	No	No
Turbidity	Yes	Yes	Yes
Taste/Odor/Color - *Chlorine/iodine* - *Natural Organic Material*	Excellent	Excellent	Moderate
P248 Capacity *(cleanings required)*	300L	1000+L	300L
Max Flow Rate	350 mL/min	2000 mL/min	1200 mL/min

4.3 Flat Filter Project Conclusions

Following the evaluations of the completed beta prototype filters, one of each of the three different configurations was fabricated and sent to ONR as samples for visual evaluations. A final project review meeting was scheduled where CDI presented the findings of this development effort. The advancements in performance acquired through a transition from the current IWPS Microfilter to the proposed flat-filter design include:

MF FLAT-FILTER:

- Significant increase in flow rate from 1200 mL/min to 2000 mL/min
- More than triple the NSF P248 capacity from 300L to over 1000L
- A qualitative increase in taste/odor/color removal despite the reduced contact time
- Increased durability with survival of 10 freeze/thaw cycles and multiple drops from 6 feet to concrete

UF FLAT-FILTER

- Single pass purifier device capable of removing all 3 classes of microorganisms
- A qualitative increase in taste/odor/color removal despite the reduced contact time

- Increased durability with survival of 10 freeze/thaw cycles and multiple drops from 6 feet to concrete

In addition, a proposal was presented requesting that additional funding be supplied in order to evaluate alternatives to the use of ultrafiltration membranes for achieving a single pass water purifier within the flat-filter model. A formal proposal was delivered and accepted thereby allowing CDI to pursue this effort as part of a project extension. This work is described in section 5.

5 Flat Filter Project Extension

5.1 Introduction

The vision for the flat filter project has always been to create a fast flowing, "scoop-and-go", single pass, drink-through personal water purification unit that can meet the standards outlined in NSF P248. The approach taken thus far has relied on the utilization of single layer MF and UF flat sheet membrane to remove all bacteria and virus from feed water. The initial effort led to success in achieving complete removal of bacteria and protozoa at higher flow, greater capacity, and increased durability, when compared to the current IWPS. However, some fundamental issues with the approach were identified during the development effort:

- MF materials possess desirable flow rate, but provide insufficient viral efficacy requiring oxidant addition
- UF materials provide greater full microbiological removal, but have borderline flow rates

In order to troubleshoot these issues an extension effort was launched. The vision for this extension was to develop a faster flowing UF membrane that would remove 1-3 log of virus from feed water placed upstream of an adsorbent layer that would remove any remaining virus not initially excluded by the membrane. The testing process was divided into three tasks: down selection of materials; small scale testing of combined materials; scale up to a breadboard device for evaluation in accordance with NSF P248.

5.2 Task 5.1: Material Down-Selection

The first step in this process was to select candidate products for the rejection layer. This was done by identifying the fastest flowing of the UF membranes that were characterized for the initial effort but rejected for falling short of the desired 4 log viral reduction. Four (4) products consisting of one of two materials were selected for consideration. Images of these two materials are shown in Figure 21, and a brief summary of each product is provided below:

- KOCH HFM-180: The membrane used in these modules consists of a semipermeable polyvinylidene difluoride (PVDF) layer cast on backing material, with a claimed pore size of 100 KDA.

- SEPRO PV400HB: Also made of PVDF, with a claimed pore size of 75 KDA. This membrane exhibited high permeability upon initial testing.

- GVS (FORMERLY MAINE MFG., FORMERLY GE WATER) PES 0.03 μM: Made of polyesthersulfone (PES) with a claimed pore size of 0.03 μm.

- STERLITECH PES MEMBRANE FILTERS, 0.03 MICRON: Made of what is most likely the same PES material as the GVS product. 0.03 μm claimed pore size.

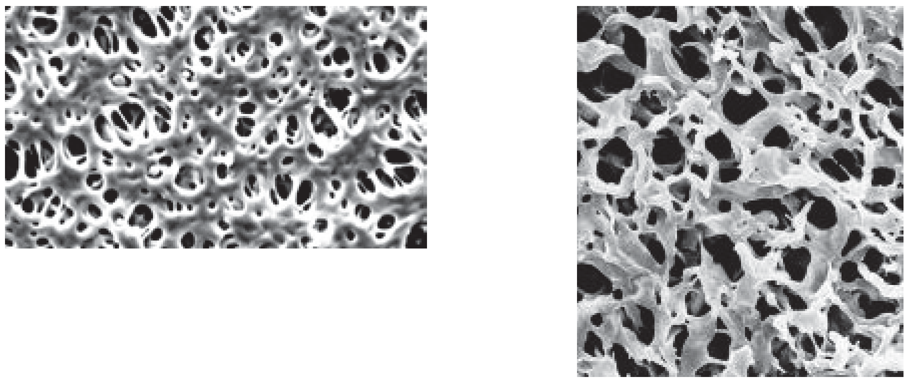

Figure 21. 0.03 μm PES Membrane (left), PVDF membrane (right) EM images

Once selected, each product was retested for flow-pressure and viral removal efficacy characteristics, the results of which are shown in Table 7 and Figure 23. All material testing for Task 5.1 was performed using 0.0017 m^2 discs. Unless otherwise specified, all flow rate and volume results have been adjusted to reflect expected measurements at full scale (0.057 m^2).

Table 7. Comparison of the efficacy and permeability of candidate UF membrane materials at a feed pressure of 3 PSI.

Rejection Layer Material	Actual Flow Rate (mL/min)	Permeability (LMH/psi)	Flow Rate Full Size (mL/min)	Viral LRV
GVS PES 0.03 μm	22.4	258	734	3.03
Sepro PV400HB	60	692	1965	2.27
KOCH HFM-180	7.2	83	236	3.94
Sterlitech PES0033001	18	208	590	2.50

Based on the results seen in Table 7 and Figure 23, GVS PES 0.03 μm (GVS PES) seemed to be the best candidate. Although Sepro PV400HB initially showed promise as a candidate material with high permeability, it also exhibited a rapid fouling rate, which was a major disqualifier for future consideration.

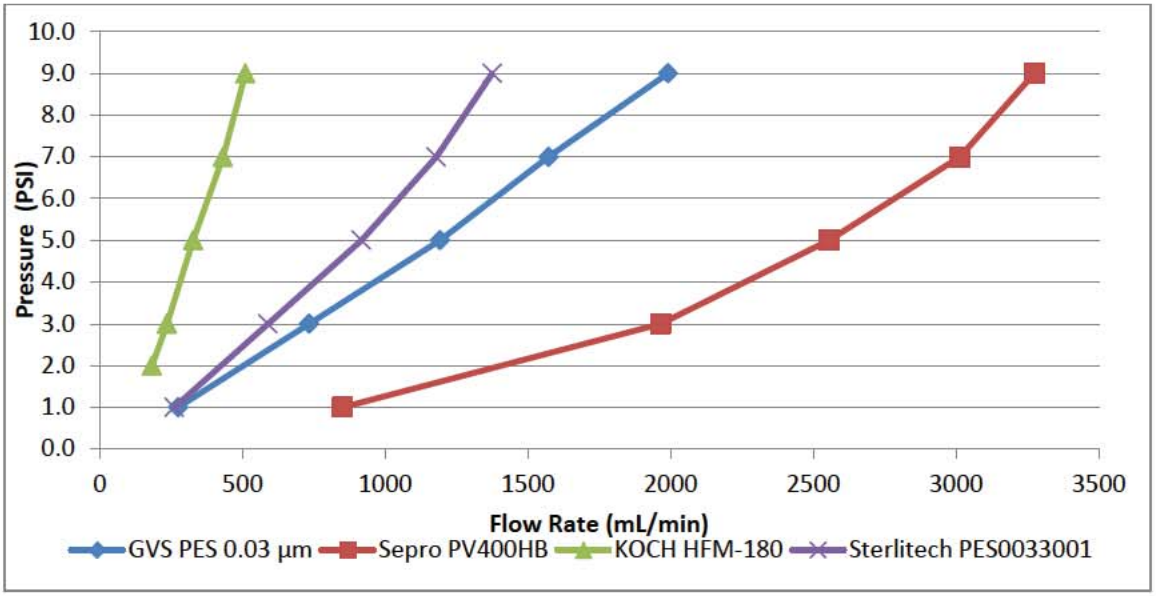

Figure 22. Flow vs. Pressure Drop for UF membrane Candidate Materials

Seven (7) adsorbent materials were evaluated at CDI, including four (4) flat sheet products from Ahlstrom, a pleated cartridge from KX technologies, and two (2) flat sheet materials provided by Liquidity Corporation. A summary explaining the utilized technology in each product is provided below:

AHLSTROM: The four (4) products surveyed from Ahlstrom are designated with product names consisting of four-digit numbers: 5283; 5284; 5288 and 5289. All four primarily consist of Ahlstrom's patented Disruptor® technology, which is composed of aluminum oxide hydroxide as shown in Figure 24. The adsorbent properties of this material are a result of the electrokinetic potential of Al^{3+} which resides on the surface of the nanofibers which ultimately form a crystalline structure. 5283 is the most basic and lowest cost of the three products, composed solely of their patented Disruptor material. 5284 is also composed of Disruptor HS with carbon as an additive. 5288 contains silver as an additive, while 5289 is supplemented with both carbon and silver, making it the most expensive of the four products.

Figure 23. Ahlstrom Disruptor ® (Aluminum Oxide Hydroxide) EM Image

LIQUIDITY: The two Liquidity products considered for use were named "USA" and "Asia". These products were composed of a proprietary adsorbent technology and little information about mode of action was provided.

KX TECHNOLOGIES: The cartridge product from KX Technologies that was considered for possible adaptation to flat sheet application was a 3-inch FACT® Media (EM image show in figure 4) cartridge. This media utilizes chemically modified, powdered, activated carbon immobilized by fibrillated nanofibers which can be as small as 50 nanometers in diameter.

Figure 24. EM Image of KX FACT® membrane (photo by KX Technologies)

All products were initially tested for permeability and viral removal kinetics, the results of which can be seen in Table 8 and Figure 26. Taking these measurements into account, three products from Ahlstrom (5283, 5284 and 5289) were selected for further consideration and testing. It should be noted that the KX Technologies 3" cartridge also performed well, but because it's fixed size cartridge configuration made it difficult to combine with flat sheet materials, this candidate was designated lower priority than flat sheet counterparts at this stage of development.

Table 8. Efficacy and permeability comparison of candidate adsorbent materials at a feed pressure of 3 PSI.

Filter Info	Flow Rate (mL/min)	Permeability (LMH/psi)	Flow Rate at Full Size (L/min)	Viral LRV
Ahlstrom 5283	244	2814	7.99	4.54
Ahlstrom 5284	264	3045	8.64	5.07
Ahlstrom 5288	240	2768	7.86	3.71
Ahlstrom 5289	188	2168	6.15	5.08
Liquidity USA	NA	> 6000	> 10 L/min	1.70
Liquidity Asia	NA	> 6000	> 10 L/min	NA
KX technologies 3" Cartridge	620	219	0.62	4.70

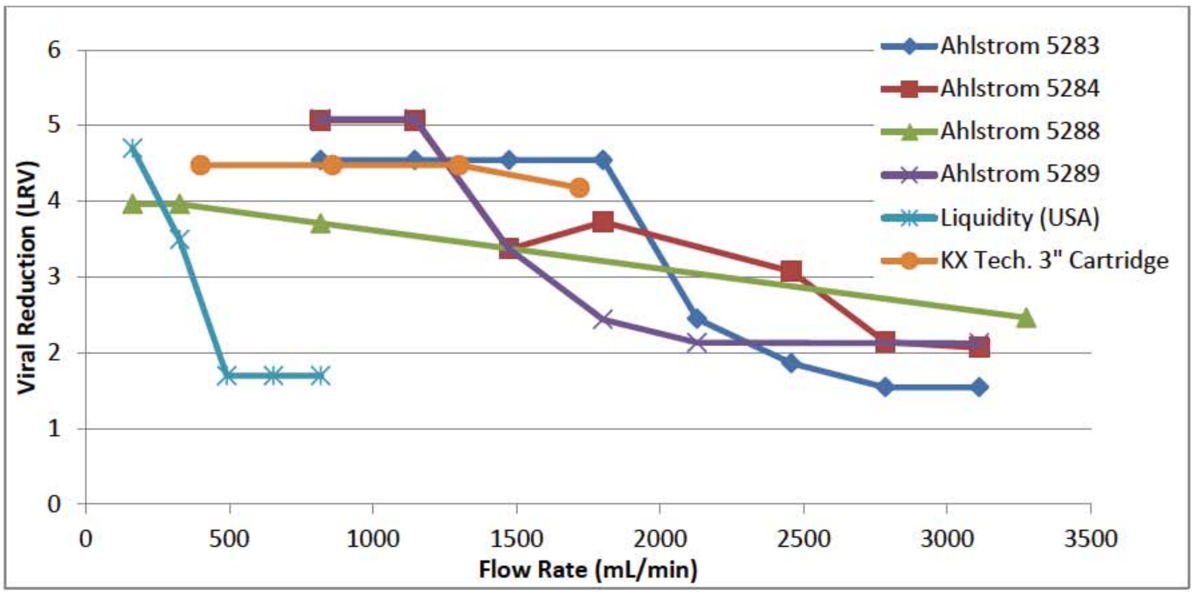

Figure 25. Comparison of viral removal kinetics achieved by adsorbent candidate technologies.

Another important metric used to evaluate in these down selected materials was viral removal capacity. Keeping flow rate constant, Ahlstrom 5283, 5284, 5288 and 5289 were challenged with virus seeded feed water while collecting viral efficacy samples every 8 liters. As can be seen in the results shown in Figure 27, all 4 materials exhibited similar capacity. Considering that Ahlstrom 5289 was the most expensive product it was eliminated from consideration, leading to the final selection of Ahlstrom 5283 and 5284 as the two candidates with which to move forward testing combinations of materials. Although there was no observed advantage in performance with Ahlstrom 5284, its carbon content was thought to be potentially beneficial for the removal of chemical contaminants and natural organic matter, thus justifying its inclusion in future testing.

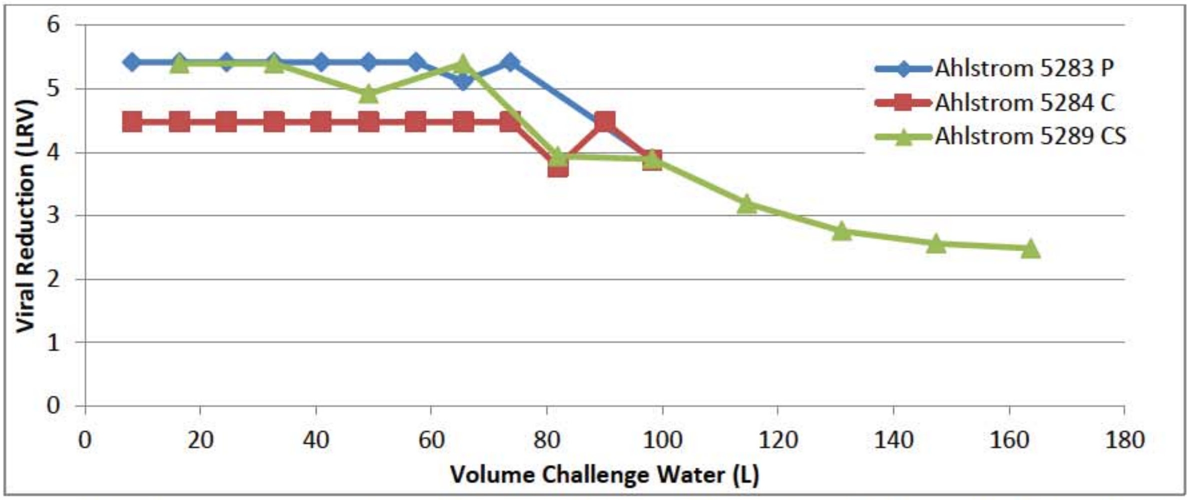

Figure 26. Comparison of viral removal capacity achieved by selected adsorbent candidates.

5.3 Task 5.2: Small Scale Testing of Combined Materials

During this phase of testing, the two selected adsorbent layer candidates [redacted] were combined with the selected rejection layer (GVS PES) in various configurations in order to determine the optimal design with which to proceed into breadboard device evaluations.

As with Task 5.1 all of the experiments included in Task 5.2 were performed using 0.001734 m^2 housings. Within these housings the two different layers were combined in several different configurations including:

[redacted]

A diagram of the breadboard test apparatus is shown in Figure 28. As illustrated, a T-valve was placed between the rejection layer and the adsorbent in order to allow for sample collection and efficacy measurements after treatment by each layer. Similar to the characterization of individual materials, testing for these combined layers included flow-pressure analysis and viral efficacy/capacity challenges in both deionized water and/or General Test Water Type 1 (GTW1).

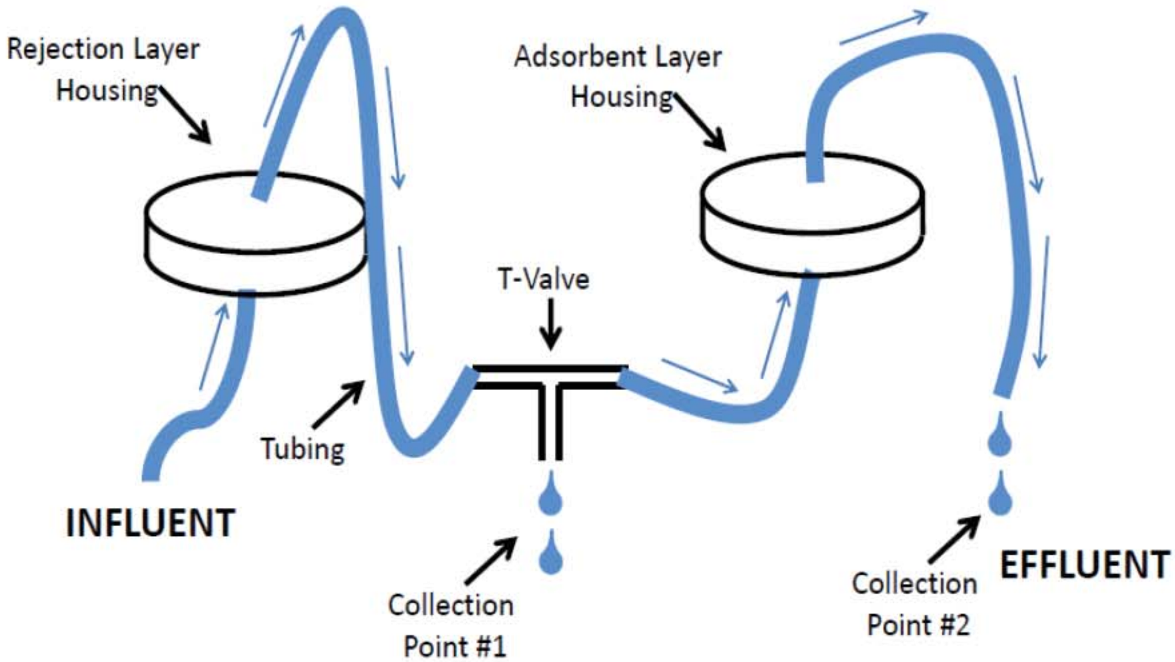

Figure 27. Schematic of isolated breadboard test apparatus.

Upon performing a flow-pressure analysis (Figure 29) on a single piece of rejection layer combined with a single piece of adsorbent, it was discovered that system permeability was determined exclusively by the permeability of the rejection layer and virtually unrestricted by the adsorbent material.

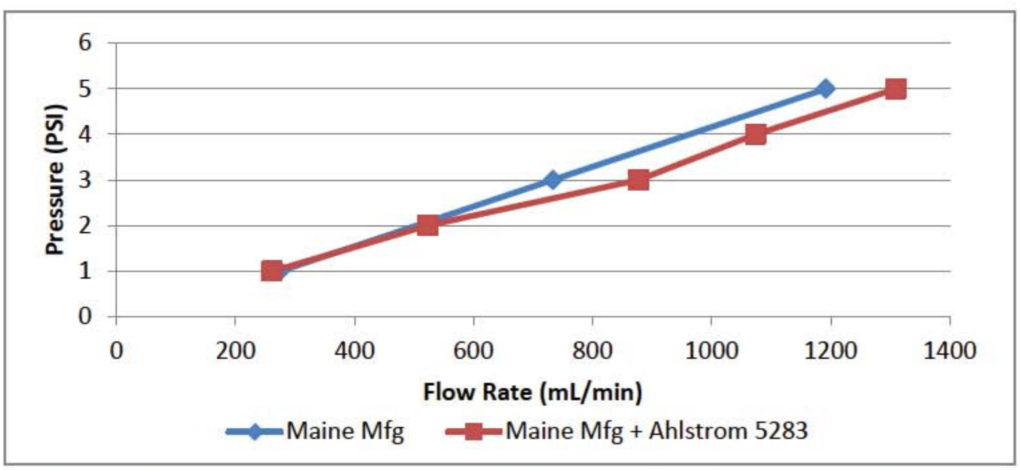

Figure 28. Flow vs. pressure characteristics of rejection layer (Maine Mfg.) alone and combined with an adsorbent.

The next detail to address in the testing process was the measurement of viral removal kinetics when the GVS PES rejection layer was paired with the [redacted] adsorbent. Three flow rates were selected in order to measure combined material performance at both slower and faster flow scenarios. Results of these tests, which are shown in Table 10, illustrated two important lessons for consideration:

- Rejection layer efficacy was prone to high variability, which is thought to be explained by variation in pore sizes between pieces of PES membrane
- [redacted] displayed slightly superior removal efficacy at faster flow rate, which may be attributable to increased alumina content, leading to increased absorptive capacity

In light of these observations it was decided that, due to the lower cost in addition to slightly superior adsorbent capacity, [redacted] was the best candidate to proceed with for the final experiments of the testing process.

Table 8. Viral removal kinetics achieved in deionized water for an isolated rejection layer and when combined with a single layer of Ahlstrom 5283 adsorbent.

Separated Housings	Flow Rate (mL/min)	Influent (pfu/mL)	Rejection Layer (LRV)	Combined (LRV)
[redacted]	655	4.18E+05	1.41	4.21
	983	4.18E+05	1.17	4.45
	1310	4.18E+05	1.26	2.72
	655	3.90E+04	0.22	4.37
	983	3.90E+04	0.29	4.31
	1310	3.90E+04	0.17	4.42

The next step in the testing process was to challenge paired materials with GTW1. The first experiment with this configuration was performed using one piece of each material placed in a single housing. Keeping feed pressure constant at 3 PSI, the combined layers were challenged with an influent stream containing a natural organic matter (NOM as tannic acid) concentration on the high end of the specifications detailed for NSF-P248 GTW1 (2 mg/L TOC). Feed water was also seeded with virus and effluent was collected for efficacy analysis approximately every 66 liters. Table 11 contains the results of this test, which indicate that the added NOM both slowed flow rate and significantly reduced viral retention capacity. Figure 30 provides photographs of both layers used in the experiment. The adsorbent layer is stained brown suggesting that it is removing NOM from the contaminated feed water. It is hypothesized that as the reduced viral capacity observed is directly related to the materials propensity to remove tannic acid which is likely competing for the same active sites.

Table 9. Viral removal capacity achieved through the combination of selected GVS membrane and Ahlstrom 5283.

Single Housing	Volume (L)	Pressure (PSI)	Flow Rate (mL/min)	LRV
(b) (4) [redacted]	0	3	537	> 4.00
	8	3	537	3.14
	66	3	511	< 3.0
	131	3	459	< 3.0

(b) (4) [redacted]

Figure 29. Images of the filter materials (b) (4) [redacted]

Taking into account this high sensitivity to NOM, the next experiment performed with the addition of a second separate 47mm housing in order to accommodate two (2) layers of (b) (4) [redacted] adsorbent downstream of a single piece of GVS PES membrane. As a single layer of adsorbent failed after a relatively low volume of high-NOM GTW1, the NOM concentration was reduced to a more standard level for GTW1 (0.2 mg/L TOC). Results and images for this experiment are shown in Figures 31 and 32, respectively. Despite the rejection layers low viral removal on its own, viral reduction requirements (> 4 LRV) and flow rate targets (> 200 mL/min) were maintained through the treatment of over 230 liters of feed water.

Images of adsorbent layers in Figure 32 show that the first layer of (b) (4) [redacted] was completely saturated with tannic acid, while the second (downstream) layer some white spaces indicating that not all of the alumina had been used up. The uneven pattern of use may be a result of a trapped air bubble or improper flow distribution. The evidence provided by this experiment further supports previous postulates concerning the fouling potential of organics on the prototype as a whole. At this point in development, it became clear that a mechanism for organics removal would most likely be needed in order for the flat filter to successfully treat the more demanding GTW3 (10 mg/L TOC).

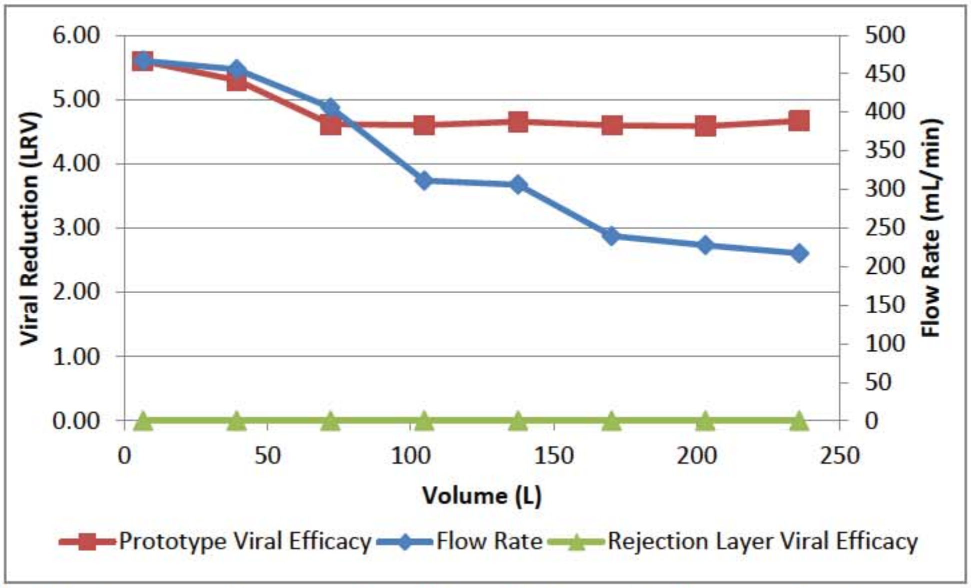

Figure 30. Viral removal capacity achieved through the combination of the [redacted] membrane and two (2) layers of [redacted] when treating GTW1 with 0.185 mg/L TOC

[redacted]

Figure 31. [redacted]

With the successful down selection of both rejection and adsorbent layers completed the development effort progressed into Task 5.3 where larger scale prototypes were fabricated and evaluated in accordance with NSF P248.

5.4 Task 5.3: Breadboard Evaluations

In this task, larger scale prototypes were used to further evaluate performance against NSF P248 test requirements. Both the selected [redacted] combination and the postponed [redacted] combination were tested for GTW2 capacity during this task in order to make a final determination of what design would be used for breadboard device fabrication.

This process started by leveraging in-house engineers to construct a test fixture (Figure 33) with the capability of housing 0.0121m^2 pieces of material (21% of full scale). This set-up was used to examine the effectiveness of the GVS membrane as a pre-filter to a 3 inch KX cartridge in treating a contaminated GTW2 feed. After an initial evaluation with GTW1 confirmed that there were no leaks in the system, GTW2 containing virus was applied at a feed pressure of 3 PSI. Unfortunately, no significant viral reduction was observed beyond 2 liters of GTW2 and, given that the 3 inch cartridge possessed a surface area equivalent to the maximum likely to be incorporated into a final filter design, this material was removed from consideration for the time being.

Table 10. GTW2 capacity measurement of GVS/KX combination prototype.

Water Type	Volume (L)	Flow Rate (mL/min)	Viral Reduction (LRV)
GTW1	1	140	4.63
GTW2	2	76	4.77
GTW2	4	40	0.51

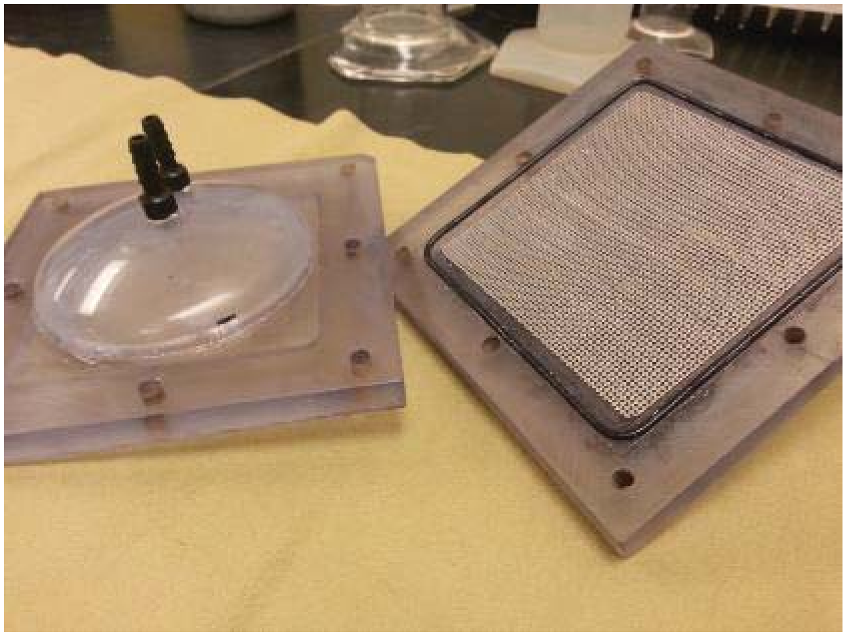

Figure 32. Moderate scale test housing (0.0121m^2 of surface area per sheet).

While this apparatus was useful for testing with single pieces of material, it was unable to properly seal when housing more than one sheet of material. For this reason a separate set of text fixtures were build, 0.02138 m^2 (37% full scale), and used to construct a breadboard system with 3 separate housings as shown in Figure 34. This system included a single layer of [redacted] rejection layer in the first housing (influent end), followed by 2 sandwiched layers of Ahlstrom 5283 in the second housing, with an additional single layer of [redacted] in the third housing (effluent end).

For breadboard device evaluations, test dust was not added to the GTW2 challenge water. This modification was made because previous testing has shown that recovery achieved during cleaning cycles will allow the final filter design to have a capacity in excess of the desired 300 liters in relation to flow rate. In addition to this, the test dust does not adversely affect viral reduction. With the primary goal of this characterization being the determination of GTW2 viral removal capacity of the breadboard device and the concerns associated introducing contamination or damaging seals with disassembly/reassembly for cleaning cycles, it was necessary to proceed without the addition of test dust.

Figure 33. Breadboard system consisting of a series of test fixtures capable of housing multiple layers with a surface area of 0.0214 m^2 each.

Although the breadboard device did possess the capability to remove all virus from feed GTW2, this system became overwhelmed over time. This system design did outperform the KX prototype with a total volume of 5-20 liters of GTW2 successfully treated to microbial reduction targets falling short of the 150 liter target. Photographs of each individual layer, shown in Figure 34, give a clear representation of the level of organic saturation that occurred throughout the 67 liter experiment.

Table 11. Flow vs. pressure characteristics of the breadboard system.

Breadboard System (0.02138m^2/Layer)	Pressure (PSI)	Flow Rate (mL/min)	Permeability (LMH/PSI)	Flow Rate* (mL/min)
(b) (4) [redacted]	1	100	281	266
	1.5	160	299	425
	2	200	281	531
	2.5	260	292	691
	3	312	292	829

*Mathematically adjusted to full scale.

Table 12. Viral removal efficacy of breadboard system when treating NSF P248 GTW3.

$0.02138 m^2$ Housings	Volume (L)	[redacted]	System (LRV)
[redacted]	5		4.85
	21		< 3.00
	40		< 3.00
	64		< 3.00

* Virus had already been removed

Figure 34. Flow rate characteristics observed [redacted]

[redacted]

Figure 35. Images of the different filter layers [redacted]

The breadboard device's sensitivity to the high concentrations of organic material (10 mg/L TOC as tannic acid) make continuation into alpha prototyping unwarranted at this time. However, with the development of an effective NOM pre-filter there is strong reason to believe that this approach to flat filter design would achieve the desired system characteristics.

5.5 Extension Effort Conclusions:

The flat filter IWPS has the potential to be an incredibly useful and efficient system for water purification, but has very limited effectiveness when treating feed water containing a high level of NOM. Additionally, upon exposure to [redacted] (b) (4) rejection layer lost virtually all effectiveness for stopping virus. With this being the case it would seem more advantageous to evaluate more fast flowing UF candidates or use an MF membrane for the rejection layer in order to achieve faster flow rate. Regardless of what approach is taken with the rejection layer, this system would require a mechanism for NOM removal in order to pass NSF-P248.

6 Conclusions

The development efforts performed during the course of this project successfully demonstrated the viability of replacing traditional cylindrical filters with a more ergonomic flat-filter design. Several advancements over the currently fielded IWPS system were proven out. First, with the utilization of a microfiltration flat sheet material where gains in performance were made in the areas of:

- Significant increases in flow rate from 1200 mL/min to 2000 mL/min;
- More than triple the NSF P248 capacity from 300L to over 1000L;
- Qualitative increases in taste/odor/color removal despite the reduced contact time;
- And, increases in durability with survival of 10 freeze/thaw cycles and multiple drops from 6 feet to concrete

The second area of advancement was in the pursuit of the ultimate goal of developing a single pass water purifier capable of meeting the needs of the US Marine Corps. Significant advancements were made in showing the feasibility of achieving this target in a flat-filter device with the implementation of an ultrafiltration membrane that was found to be capable of achieving microbial log reduction in both GTW1 and GTW2. One each of the fully functional beta prototypes (MF and UF) were delivered to ONR. The flow rate of the ultrafiltration prototype (350 mL/min maximum) was high enough to meet the minimum flow rate spec of 200 mL/min, but is still disappointing from a user standpoint when relying exclusively on membrane rejection to achieve viral reduction.

As such, additional work was done to explore the ability to improve the flow rate of a single pass flat-filter purifier through the synergistic combination of adsorbent sheet materials for viral reduction and microfiltration membrane for turbidity, protozoa, and bacterial removal. This system was developed into a breadboard device and achieved the required 3 log protozoa, 6 log bacteria, and 4 log virus reduction in both GTW1 and GTW2 with an initial flow rate of greater than 800 mL/min (two fold increase over the UF beta prototype – 350 mL/min). The breadboard device was found to successfully treat the equivalent of 260 liters of GTW1 while maintaining the desired microbial reduction ratings however, the high concentration of organics (10 mg/L

TOC – tannic acid) of GTW2 was found to have a significant effect on capacity in this more challenging water (< 20 L GTW2).

Cascade Designs, Inc. has strong reason to believe that an effort focused on the development of flat sheet materials specifically for pre-filtration and removal of natural organic matter (NOM) would present options for further extending the capacity of this adsorbent/MF design. If capacity could be extended, the resulting purifier would have great commercial potential for both military and outdoor recreation/travel markets.